

ENRICO FERMI AND THE PHYSICS AND ENGINEERING OF A NUCLEAR PILE: THE RETRIEVAL OF NOVEL DOCUMENTS

S. ESPOSITO AND O. PISANTI

ABSTRACT. We give a detailed account of the recent retrieval of a consistent amount (about 600 pages) of documents written by Enrico Fermi and/or his collaborators, coming from different sources previously unexplored. These documents include articles, patents, reports, notes on scientific and technical meetings and other papers, mainly testifying Fermi's activity in the 1940s about nuclear pile physics and engineering. All of them have been carefully described, pointing out the relevance of the given papers for their scientific or even historical content. From the analysis of these papers, a number of important scientific and technical points comes out, putting a truly new light on the Fermi's (and others') scientific activity about nuclear piles and their applications. Quite unexpectedly intriguing historical remarks, such as those regarding the relationships between U.S. and Britain, just after the end of the war, about nuclear power for pacific and/or military use, or even regarding long term physics research and post-war research policy, emerge as well.

1. INTRODUCTION

The name of Enrico Fermi is universally associated to the successful development of the self-sustaining nuclear chain reaction culminated, at first, in the operation of the first controlled nuclear pile in Chicago on December 2, 1942 and, then, in the realization of the first nuclear explosion in the Trinity test of the Los Alamos laboratory on July 16, 1945. The acknowledgment of the fundamental role played by the Italian scientist in this project comes directly from the papers written by Fermi himself, and collected in the 1960s by his former collaborators [1], but especially from the numerous and detailed accounts by the people who worked with him in that project. In fact, as it is natural to expect, the work on nuclear fission carried out during the war years was classified, so that only essential reports were written on that work, and only part of them was declassified after some time, and made publicly available. These reports testifying Fermi's activity, as available in the first 1960s, were published in the *Collected Papers* of Ref. [1]. However, by giving an accurate look at this material, it results quite evident that what published, though amounting to a large figure, is not the complete story. This conclusion comes out not only by assuming the existence of possible documents, earlier classified, but also by analyzing and cross-checking different testimonies (among the others, we quote for example the book written by Emilio Segrè [2] and the recollections by Herbert L. Anderson and Albert Wattenberg in Ref. [3]).

A careful work devoted to investigate towards such a direction has now been performed by one of us (S.E.) and has lead to the retrieval of a consistent amount of papers, reports or other documents written by Fermi himself and/or his collaborators, directly pointing out the peculiar activity of the Italian scientist about different aspects of Nuclear Physics, but *not* limited to the scientific point of view (in a strict sense).

We have completed the analysis of all this novel material, amounting to about 600 pages, and present here the results of this study.

The major sources of the documents are the following:

1. the Albert Wattenberg Papers at the University Library of the University of Illinois at Urbana-Champaign;
2. the United States Patent and Trademark Office;
3. the Papers of Sir James Chadwick at the Churchill Archives Centre in Cambridge (U.K.).

In the archives of the University of Illinois at Urbana-Champaign a number of papers are deposited donated by Albert Wattenberg (1917-2007), a former collaborator of Fermi, who collected documents pertaining to the Manhattan Project. Part of them were retrieved by Wattenberg as joint editor of the *Collected Papers* by Fermi, and then published in Ref. [1]. However, among these documents we found many unpublished notes and reports, all dealing with the activity by Fermi and others on nuclear fission topics, ranging from 1942 to 1944. In particular we have found 23 notes on meetings of different Councils, where explicit interventions by Fermi were annotated, 2 scientific/technical reports written by Fermi and collaborators, 5 periodic reports edited by Fermi and others, 1 anonymous scientific/technical report classified by Wattenberg among the Fermi papers.

In the U.S. Patent Office, instead, we have found the most important papers, from a strictly scientific viewpoint, that is the papers for 15 patents filed up to 1952 (the vast majority ranging from 1944 to 1946), all but two directly dealing with nuclear reactors. In practice, all these patents were issued many years after their application to the competent office, some of them being even posthumous, and were never published (in Ref. [1], for example, except for one case, they hadn't even been mentioned).

Finally, among the papers deposited by Sir James Chadwick at the Churchill Archives Centre in Cambridge (U.K.), the most relevant one related to Enrico Fermi is a complete version of the set of lectures given by Fermi at Los Alamos in 1945 on Neutron Physics, containing some material *not present* in the known "American" version (published on page 440ff of Volume II of Ref. [1]).

Other "minor" documents have been recovered as well; all the material not published or mentioned in the Fermi's *Collected Papers* and now retrieved will be discussed in some detail in the following.

2. THE PATH TO THE EXPLOITATION OF NUCLEAR ENERGY

In order to put in the right context what is the object of the present analysis, it will be preceded by a rapid summary of what was known about the activity of Fermi on nuclear fission and related topics before our recent retrieval.

2.1. The discovery of the fission of uranium and the possibility to produce a chain reaction.

It has been known for many years that vast amounts of energy are stored in the nuclei of many atomic species and that their release is non in contradiction with the principle of the conservation of the energy, nor with any other of the accepted basic laws of physics. In spite of this recognized fact, it was the general opinion among physicists until recently that a large scale release of the nuclear

energy would not be possible without the discovery of some new phenomenon. [4]

Such a new phenomenon, as mentioned by Fermi in one of his reviews of 1946, was that observed by Otto Hahn and Fritz Strassmann in the Fall of 1938 at the Kaiser Wilhelm Institute in Berlin, when bombarding the uranium nucleus with neutrons from a radium-beryllium source. The correct explanation of the Hahn and Strassmann experiments was soon given by Lise Meitner and Otto R. Frisch who interpreted the observed phenomenon as due to the splitting of uranium, from which two elements formed, each of approximately half of its original mass. The mass which “disappeared” was assumed to be converted into energy, according to Einstein’s theory of relativity.

The news of the novel phenomenon reached the other side of the Atlantic Ocean just after Fermi and his family arrived in America, after receiving the Nobel Prize in Stockholm.

Niels Bohr, who had come for a stay at Princeton, was on his way to attend a conference in Washington. [...] By the time he was ready to leave Princeton, Bohr had heard the results of Frisch’s experiments. It was a most exciting development. [5]

Willis Lamb was in Princeton at that time and, after heard from Bohr of this breaking news, he went to Columbia University and communicated it to Fermi [2]. Quite independently, according to Anderson’s recollections,

on his way to Washington, Bohr thought it would be a good idea to drop by and see Fermi to tell him about the exciting new physics. He came to the Pupin Physics Laboratory looking for Fermi. [...] He didn’t find Fermi; he found me instead. I was the only person around. He hadn’t see me before but that didn’t stop him. He grabbed me by the shoulder and said, “Young man, let me tell you about fission.” [...] I had heard enough to catch the excitement. [...] When Bohr left I felt I had something to tell Fermi. [...] “Professor Fermi, I’ve come to tell you that I have just seen Professor Bohr. He was looking for you and he told me some very interesting things.” Fermi interrupted me. A smile broke out and he said, “Let ME tell you about fission.” Then I heard again, but this time much more graphically, how the energy would appear when the uranium was split and the pieces flew apart by Coulomb repulsion. [5]

After the news spread out, many physicists (including Fermi and collaborators) confirmed the results by Hahn and Strassmann and proved true the interpretation and suggestions by Frisch, working rapidly for a better understanding of the phenomenon.

In the spring of 1939 it was generally known that a fission that can be produced by the collision of a single neutron with a uranium atom was capable of producing more than one new neutron, probably something of the order of two or three. It was felt at that time by many physicists that a chain reaction based on the uranium fission was a possibility well worth investigating. [4]

The idea of a nuclear chain reaction able to liberate energy on a large scale came to Leo Szilard as early as in 1933-4, when it was believed that beryllium

(instead of uranium) was unstable and that neutrons would split off when this element disintegrated. This proved soon incorrect, but the possibility to create a process that would emit more neutrons than were absorbed (or, in other words, with a multiplication or reproduction factor greater than one) came back into the picture when the fission of uranium was discovered. This was promptly recognized by Szilard who, according to Anderson [5], “was very anxious to work with Fermi, or at least to have discussion with him” in order to achieve effectively a chain reaction.

2.2. Natural uranium and graphite. In 1939 a number of experiments were performed to put the problem of fission on a quantitative basis. The first important fact to be realized was that the cross section for neutron fission was higher for low energy neutrons, while the second one was that the key isotope of uranium involved in the fission induced by slow neutrons was the rare one of mass 235, instead of the most abundant ^{238}U . The problem was, however, complicated by the fact that, besides producing fission, slow neutrons can also give rise to the production of the radioactive isotope ^{239}U by simple capture. In particular the capture of neutrons with thermal energies (thermal neutrons) was proved to be due to a strong resonance absorption at somewhat higher energies [6]. Such a process competes with fission in taking up the neutrons which are needed to sustain a chain reaction, so that a major problem in making the chain reaction to be effective was to avoid losses due to this absorption.

In any case, the first basic point to be cleared up was the choice of the fissile material to be used and, in this respect, two alternatives were opened at the end of 1939. The first one was the separation of ^{235}U from the natural uranium, thus eliminating the absorption by the most abundant isotope ^{238}U . Obviously, for this method to work, the major difficulty for that time was to produce large quantities of the isotope needed. The alternative choice was, instead, to use directly natural uranium, with the evident drawback caused by the undesirable absorption of neutrons by the most abundant isotope, which may lower significantly the multiplication factor for the self-sustaining reaction to be achieved. The problem with both the alternative methods were serious, and Fermi chose to work out the one where more physical effects should be understood and kept under control, i.e. he decided to study the possibility of a chain reaction with natural uranium. It is quite interesting to observe that Fermi was very confident that such a way was the right one:

“Herbert,” he said, “if you stick with me we’ll get the chain reaction first. The other guys will have to separate those isotopes first, but we’ll make it work with ordinary uranium.” [5]

Such an attitude, as usual for him, came from the appropriate quantitative results he and his collaborators obtained from an extensive experimental work. Here, as already mentioned, the discriminating factor was the slowing down of the incident neutrons, which makes more effective the cross section for fission with respect to that for absorption.

The problem of the slowing down of neutrons and its effect on the development of neutron-induced nuclear reactions (and, in particular, the production of radioactive elements) had been the subject of intense and fruitful researches by Fermi and his group in Rome as early as 1934 [7], and lead to several important papers, collected

in Ref. [1]. A patent for the practical applications of the results obtained was as well issued; the interesting subsequent anecdotes related to this patent have been narrated in Ref. [2]. It was recognized that the most efficient way to slow down neutrons was to pass them through hydrogen, the lightest chemical elements present in water, paraffin, etc., so that the obvious conclusion for getting a reproduction factor high enough for a chain reaction was to disseminate uranium powder in water. However, measurements revealed [8] that thermal neutron absorption by hydrogen was too large for water to make it a usable medium for slowing down neutrons in a chain reaction, since that absorption (leading to formation of deuterium) would lower substantially the multiplication factor. Thus, other light elements should be taken into consideration.

Out of Szilard's thinking came the idea of using graphite instead of water to slow down the neutron. [...] Fermi had also been thinking about graphite. [5]

Measurements showed [9] that the absorption of neutrons on graphite was small enough to make it the obvious choice for a material for slowing down the neutrons, so that Fermi set forth also the basic theoretical techniques for describing the behaviour of neutrons in such substances. It was also shown that, after the neutrons reached thermal energies, a second diffusion process began in which the neutrons continued to diffuse through the material until they either escaped or were absorbed. The advantages of graphite against water, as a moderator for neutrons, came out from experiments with a pile of graphite aimed at measuring the absorption of carbon [10]. In such a pile the neutrons were slowed down more slowly than in water, but once they reached thermal energies the neutrons would diffuse longer and reach greater distances from the source. As a consequence, a physical separation of the thermal neutrons from higher energy ones could be obtained, and this property was later used by Fermi in many different ways.

2.3. Experimental piles. At this point of the story, the next step was to design a chain reacting pile that would work, and, to this end, a number of experimental piles were built, early at Columbia University in New York and then at Chicago, to study directly the properties of uranium and graphite (or other moderators) in a pile.

The key ingredient was, of course, to work with sufficiently pure materials; these were obtained from different factories (with quite different degree of purity), and always were tested by Fermi and his collaborators. A chemical method, involving ether separation, was used to purify uranium [11] while the absorption of neutrons by graphite was especially measured.

Graphite bricks were stacked into the so-called “sigma pile” (denoted with the Greek letter “sigma”), designed to measure the absorption cross section. A neutron source was placed near the bottom of the pile and indium foils were exposed at various points on the vertical axis above the source; from the radioactivity induced in these foils the absorption cross section of graphite was deduced. To this regard, standard procedures were introduced [12] by which indium (and rhodium) foils could be calibrated in order that the measurement of their radioactivity could be used to give either the slow neutron density or the slowing down density in absolute units. The graphite column erected at Columbia was also used as a source of thermal neutrons in the measurement of the absorption cross section of boron.

This element, in fact, had importance in absolute neutron measurement, because of its high neutron absorption cross section and its dependence on the inverse of the velocity of neutrons [13].

For uranium, apart from its purification, an important problem was that of resonance absorption, as mentioned before. The idea then came out of using uranium in lumps, just to reduce the resonance absorption. Also, Fermi measured the resonance absorption for uranium oxide compressed into spheres and, in particular, when these spheres were embedded in graphite [14]. Evidently, he was already thinking about experiments to test a “complete” uranium-graphite reactor.

Meanwhile, the fission of uranium induced by fast (rather than slow) neutrons was as well investigated to some extent, not only for the possibility of obtaining a fast neutron chain reaction, but also for measuring the contribution of fast neutron-induced reactions to the slow neutron chain reaction [15].

Fermi and Szilard had the very important idea of placing the uranium oxide in a lattice in the graphite, instead of spreading it out uniformly [16]. Here the problem was “to ascertain whether a given lattice of uranium oxide lumps embedded in graphite could give a divergent chain reaction if its dimensions were made sufficiently large” [17], by exercising the greatest care in keeping under control possible losses of neutrons.

In order to test with a smaller structure whether a larger one would work, Fermi invented the “exponential experiment”. Uranium was placed among the graphite bricks in a cubic lattice array, with a radium-beryllium neutron source near the bottom and indium foils exposed at various distances from it on the vertical axis. The arrangement is, thus, similar to that of the sigma pile, but the exponential pile was much larger than the sigma pile. The exponential decrease in the neutron density along the axis is greater or less than that expected due to leakage according to whether the reproduction factor is less or greater than one.

Such exponential piles were developed at Columbia in Summer-Fall of 1941 [4]; they produced results indicating that even an infinite amount of material would not lead to a self-sustaining structure, this being due mainly to the impurities in the graphite. The situation changed when, during the following Spring (1942), some new graphite was available. The last two experiments performed at Columbia, before the move to Chicago, gave encouraging results [18, 19], and definitively demonstrated an understanding of the physical effects being involved.

2.4. Achieving the first nuclear chain reaction. The National Academy of Science Committee, whose chairman was Arthur H. Compton of the University of Chicago, was charged to review the uranium projects of the United States and to judge their military importance. At the end of 1941 the Committee decided that the work made by the Fermi group using natural uranium was important and, one day before the Pear Harbor attack on December 7, 1941, the Metallurgical Laboratory was established with Compton as its scientific head in Chicago. For people working on a chain reaction using natural uranium, Chicago became the only game going and, finally, Fermi and his group at Columbia definitively moved to Chicago in April 1942.

Under Compton leadership a large number of people came too. Among them there was Szilard who worked hard getting the graphite free from neutron absorbing impurities, and Norman Hilberry, who

did a marvellous job procuring what was needed. Soon large quantities of graphite began to appear for us to test. Equally strenuous efforts were expended getting uranium in forms sufficiently pure. First we worked with uranium oxide. Then various people worked to produce uranium metal. Outstanding among those was Frank Spedding from Iowa State University. [...] Spedding's uranium was an important component of the first chain reaction. [5]

A number of engineers then came into the project to produce an appropriate and feasible design of a chain reacting system, so that a first practical problem was to “translate” the known physical achievements into a form suitable to them who had little knowledge in a field completely new. To this end, Fermi invented the notion of “danger coefficient” [20] for identifying the impurities which were dangerous for the realization of the chain reaction, due to their high neutron absorption cross section. The effect of such impurities was, then, taken into account directly on the evaluation of the multiplication factor through those danger coefficients. For example, it was determined the effect of gases in the interstices of the graphite, mainly concerning with the appreciable amount of nitrogen impurity in the porous graphite, or even the effect of the undesirable impurity of water in graphite or uranium [16].

Another problem studied was the stability of the pile against temperature changes, since the heat production in the reactor would have altered the reactivity of the pile [21].

The study of the uranium-graphite reactor was not the sole work carried out at the Metallurgical Laboratory; other possible systems were as well considered and some measurements made. This is the case, for example, of the so-called “water boiler”, that is a reactor system made of a central uranium core enriched with ^{235}U and water around it serving as a moderator [22]. Also, the multiplication factor of a uranium oxide system with a beryllium metal as neutron moderator was measured [16].

Turning back to the study of the main uranium-graphite reactor, the first important result was obtained in August 1942, when very pure uranium oxide was delivered to the Laboratory, making the reproduction factor k greater than one for the first time [23]. The 4% excess available ($k = 1.04$) effectively opened the road to the building of the first self-sustaining pile, the Chicago Pile No. 1 (CP-1).

The major engineering problem with it was the choice of an adequate cooling system with sufficiently low neutron absorption, since the “official” motivation for the project was to produce plutonium, another fissile material (other than ^{235}U) to be used also for military purposes. Indeed, “a large effort was underway for planning the pilot and production reactors, on the assumption that CP-1 would succeed” [16]. Alternative choices [24] were proposed to cool the system by gas (preferably helium), water, or even liquid bismuth, this ingenious proposal by Szilard being later set aside because of the lack of engineering experience with this material. The Chicago group definitively worked on the design for a helium cooled plant submitted by the engineers T.V. Moore and M. Leverett.

So it happened that on 15th of November [1942] we started to build the pile in the West Stacks [of the Stagg Field, in Chicago.] [...] Fermi wanted to build the pile with a shape as close to spherical as possible. This would minimize the surface/volume ratio and make

the best use of the material which would become available. [...] A major change in design came when we had news that Spedding would be sending some of his high purity uranium metal. The best place for this was as close to the center as possible. As a result, the shape of the pile was changed as we went along. The spherical shape we started with got squashed somewhat as we went along because the purity of the material we were getting was better than we had anticipated. [5]

The delivery of the Spedding's metal avoided the use of another ingenious trick proposed by Anderson, i.e. to build the pile inside an envelope made of balloon cloth to remove the air (and replace it with Carbon dioxide), in order to minimize the absorption of neutrons by the nitrogen in the air within the pile, with a gain of about 1% in the reproduction factor [25, 5].

To initiate the chain reaction, it was not necessary (as in experimental piles) to introduce in the pile a separate neutron source since, as already experimentally measured, the uranium also had a non-vanishing probability for spontaneous fission, so that it emits a few neutrons of its own. However, when the pile was building, to keep it from becoming too reactive once it began to approach the critical size, some neutron absorber was needed to control the reactivity of the chain reaction. Control rods were, then, inserted within the pile, made simply of strips of cadmium, since such element was known to be a strong neutron absorber. The pile was controlled and prevented from burning itself to complete destruction just by these cadmium rods, which absorb neutrons and stop the bombardment process of uranium. Further safety arrangements were as well conceived and set up by Fermi for the first reactor (see Ref. [5], for example), whose construction resulted to be completed about a week earlier than the director of the Metallurgical Laboratory had officially anticipated. In the afternoon of December 2, 1942, in fact, the Chicago Pile No. 1 finally got critical and a chain reaction successfully started for the first time.

We had built the pile, and Fermi had established that we could get a self-sustaining nuclear reaction that we could control in a very predictable manner. [16]

2.5. Further studies on nuclear piles during the war years. The further development in the studies on nuclear pile, during the three years 1943-1945 was of course focused on the main objective of producing weapons, so that it is natural to expect very few detailed information on these classified topics. Indeed, none of these appeared in the *Collected Papers* by Fermi [1], and our source of information is only composed of eyewitnesses (see, for example, [2]). However, quite fortunately, some reports exist that testify on part of Fermi's activity during these years, not strictly and directly related to military applications, though those reports had been classified for some time (see Ref. [1]). In the following we will briefly discuss only such known activity.

First of all, the pile was used as a suitable device for checking directly the purity of the uranium and for studying a number of features of the uranium-graphite lattice, unaccessible before [26]. However, after about three months of operation, the original CP-1 pile was explored sufficiently to learn how to rebuild it with many improvements. A second pile, CP-2, was effectively built at the Argonne site, near Chicago, in March of 1943, and several studies started to be done. These were

mainly aimed at designing an efficient pilot plant for producing plutonium or for isotope separation. Such plants were actually erected (at the end of 1943 and later on) at Oak Ridge, Tennessee (known as “Site X”) and at Hanford, Washington (known as “Site W”). An example is the designing and test of a radiation shield for the production piles to be built at Hanford, mentioned in Ref. [27].

The pile was also used as a tool to measure neutron absorption cross sections by several elements. Samples of these elements were put in the pile, and the compensating changes in control rod position were determined [28]. This method also became a routine tool for checking for neutron absorbing impurities in the materials used in reactors.

Some explicit “physics works” was, furthermore, carried out when the so-called “thermal column” was devised by Fermi and incorporated in experimental piles [29]. A graphite column was, in fact, set up on the top of a pile, where thermal neutrons could be found with substantial intensity and essentially free from those of higher energy. This led to the discovery of a novel phenomenon, that is the diffraction of thermal neutrons by graphite lattice [30], which opened the road to investigate the wave properties of neutrons [31]. The increased neutron intensity available from a pile also allowed to obtain truly monochromatic beams of neutrons for different experiments (such as, for example, the measurement of the boron cross section at a well definite neutron velocity). This was made possible by a thermal neutron velocity selector designed by Fermi at the Los Alamos Laboratory (known as “Site Y”) [32] and then built at Argonne.

The fission spectrum of uranium was also measured accurately by exploiting the slow neutrons provided by a pile, which were then absorbed by a layer of uranium. Other physical properties of ^{235}U and ^{239}Pu were as well determined [33], and these measurements, performed at Los Alamos in 1944 with the active collaboration of Chicago’s people, revealed somewhat unexpected properties of plutonium. In the same period some interesting work was also done on the theoretically possible phenomenon of “breeding” [34], namely of producing more fissionable material in a reactor than was consumed, clearly depending on the effective number of neutrons available in the chain reaction.

The increased production of heavy water in 1943 made possible to take seriously into account a proposal by H.C. Urey of April 1942 to use heavy water as neutron moderator. This led to the construction of an experimental reactor, known as P-9 and later becoming CP-3 pile, which would have much more power than CP-2, thus extending the experimental possibilities [35].

Finally, other effects were studied during 1944, ranging from the dissociation pressure of water due to fission [36] to the measurement of the amount of nitrogen in the first production pile at Hanford. An unexpected problem with the Hanford pile was also studied, and independently solved by Fermi and J. Wheeler, on the xenon poisoning, which caused the full stop of the chain reaction [37].

Further works by Fermi until the end of the Second World War concerned mainly the realization of the atomic bomb at the Los Alamos Laboratory, so that the corresponding written reports were strictly classified and not available for the *Collected Papers*. A relevant exception are the lecture notes [38] for a course that Fermi gave at Los Alamos just after the end of the war, in the fall of 1945. Here he summarized the results achieved on neutron physics, with particular reference to nuclear piles.

These lectures are, however, an example of the didactic ability of Fermi rather than a source of information about his research work.

3. NOVEL DOCUMENTS

We have indulged above on the works carried out by Fermi and his collaborators about pile physics, to give an as complete as possible overview of all the related topics tackled in the first 1940s. This has been done not only for giving an appropriate context for the documents recently retrieved, but also for a better comprehension of the novel material present in it, which we now prepare to discuss in some detail.

In order to identify the documents retrieved in different places, we have used a simple coding for them made of three or four letters determining the source archive: USP for U.S. Patents, WAT for the papers in the Wattenberg Archive and CHAD for the documents in the Chadwick Archive. The number following the USP code enumerates the Fermi patents, in chronological order. Instead, for the WAT code we have used the same cataloguing number of the Library of the University of Illinois at Urbana-Champaign; however, since in several cases this cataloguing number refers to more than one document, we have also added an additional (lower case) letter differentiating the diverse documents (the alphabetical order corresponding to the chronological order). Minor documents coming from other sources do not seemingly necessitate of additional codes.

Some of the papers just retrieved were not directly written by Fermi, but are directly related to works performed by him, such as lecture notes, reports or notes on meetings, and so on. In order to let the reader to recognize promptly these papers, we have used special symbols. In particular, we have denoted with a \diamond those where the contribution by Fermi is explicitly recognizable (typically, notes on meetings), and with a * those where such contribution can be deduced only indirectly (lecture notes or edited reports).

3.1. Patents. From the strictly scientific point of view, the most important part of the present work concerns with the retrieval of the patents authored (or co-authored) by Fermi on pile physics and engineering. Except USP1 and USP8, all the patents deal with the technical and operative construction of nuclear reactors. The activity by Fermi on this subject was early well recognized from the accounts given by the living testimonies (see, for example, Ref. [2]) and partially documented by several papers appeared in the Fermi's *Collected Papers*, as discussed above. Nevertheless, from the newly retrieved papers, a number of important scientific and technical points comes out, putting some new bright light on the Fermi's activity in the project. In practice, what Fermi *effectively* did for the success of the project is here technically documented, and very clearly emerges from these papers. It is quite impressive the fact that, just from the accurate reading of the patents, anyone who has at his own disposal the necessary materials could effectively build a working reactor, with a number of possible alternatives.

A detailed account of these patents then follows.

USP1 *Process for the production of radioactive substances* (7 pages + 2 figures),
by E. Fermi, E. Amaldi, B. Pontecorvo, F. Rasetti and E. Segrè,
filed Oct. 3, 1935 (Patent No. 2,206,634; July 2, 1940);

original patent application filed Oct. 26, 1934 in Italy (Patent No. 324,458).

“This invention relates to the production of isotopes of elements from other isotopes of the same or different elements by reaction with neutrons, and especially to the production of artificial radioactivity by formation of unstable isotopes. [...] It is an object of the present invention to provide a method and apparatus by which nuclear reactions can be carried on with high efficiency and with the heavier as well as the lighter elements. A more specific object of the invention is to provide a method and apparatus for artificially producing radio-active substances with efficiency such that their cost may be brought below that of natural radio-active materials. Our invention is based upon the use of neutron instead of charged particles for the bombardment and transformation of the isotopes.”

Indeed, in this paper, a very detailed description of the experimental results obtained by studying the radioactivity induced in a number of chemical elements by irradiation of slow neutrons is reported, along with a corresponding theoretical interpretation.

The original patent application, *Metodo per accrescere il rendimento dei procedimenti per la produzione di radioattività artificiali mediante il bombardamento con neutroni* (Method for increasing the efficiency of the processes for the production of artificial radioactivities by neutron bombardment), was submitted in Italy just after the achievement (on October 22, 1934) of the first experimental results, and later extended to U.S.A. and other countries. The intriguing story about this patent (seemingly without reference to its content), which resulted to be of fundamental relevance for the subsequent development of the atomic energy, is well described in the literature (see, for example, Ref. [2]).

Particularly interesting is the mention of the possible discovery of “transuranic” elements given in the present patent. Even here, some caution was adopted about its interpretation, as well as the theoretical interpretation of the effects induced by slow neutrons considered in the paper: “The theoretical statements and explanations are, of course, not conclusive and our invention is in no way dependent upon their correctness. We have found them helpful and give them for the aid of others, but our invention will be equally useful if it should prove that our theoretical conclusions are not altogether correct.”¹

The reference article for the material here contained is Ref. [39] of February 15, 1935 to which we refer the reader for further details. However, at least in part, specific results discussed here are somewhat different from those in Ref. [39].

USP2 *Test exponential pile* (11 pages + 11 figures),
by E. Fermi,
filed May 4, 1944 (Patent No. 2,780,595; Feb. 5, 1957).

“My invention relates to the general subject of nuclear fission and more particularly to a means and method to creating and measuring a chain reaction obtained by nuclear fission of natural uranium having a ^{235}U isotope

¹Similar sentences appear also in other patents for evident legal reasons, but here the dubious “theoretical correctness” is particularly pointed out.

content of approximately $1/139$.”

The paper contains an extremely detailed description of an atomic pile employing natural uranium as fissile material and graphite as moderator. Apart from the discussion of the theory of the intervening phenomena, a report on the very construction of such a pile (with many detailed drawings) and on the experimental test of the pile (discussing experimental data, their interpretation and possible improvements) is given. Particularly relevant is the reported “invention” of the exponential experiment, aimed at ascertaining if the pile under construction would be divergent (i.e. with a neutron multiplication factor k greater than 1) by making measurements on a smaller pile. The idea is to measure the exponential decrease of the neutron density along the length of a column of uranium-graphite lattice, where a neutron source is placed near its base. Such an exponential decrease is greater or less than that expected due to leakage, according to whether the k factor is less or greater than 1, so that this experiment is able to test the criticality of the pile, its accuracy increasing with the size of the column.

For the present paper, there is no “reference” published article, although some material appears also in the important Ref. [17] of March 26, 1942. More in general, some results are as well present in several papers of Volume II of the Fermi *Collected Papers* [1], but many details (including several figures) are reported only in the present patent.

USP3 *Neutronic reactor* (30 pages + 42 figures),
by E. Fermi and L. Szilard,
filed Dec. 19, 1944 (Patent No. 2,708,656; May 17, 1955).

“The present invention relates to the general subject of nuclear fission and particularly to the establishment of self-sustaining neutron chain fission reaction in systems embodying uranium having a natural isotopic content.”

As emphasized in *The New York Times* of May 19, 1955, this “historic patent, covering the first nuclear reactor”, is the first one issued by the U.S. Patent Office, and served as a reference for the subsequent patents on the same subject. In this long paper, the theory, experimental data and principles of construction and operation of “any” type of nuclear reactor known at that time are discussed in an extremely detailed way. Various possible fission fragments produced by the reactor, several forms of the uranium employed (metal, oxide and so on, grouped in different geometrical forms), various materials adopted as moderators, several cooling systems, different geometries of the reactors, etc. are considered accurately.

The theoretical description, centered around the achievement of a self-sustaining chain reaction, is exhaustive, and great attention is devoted to any possible cause of neutron loss, to the resonance capture of neutron and to the effect of the presence of relevant impurities in the reactor. The production chain of neutrons in the pile is described in great detail, along with the theoretical arguments underlying the exponential experiment.

The problem of the variation of the multiplication factor due to the production of radioactive elements, such as xenon, is discussed extensively. In particular it is pointed out that, although the initial production of xenon lowers the multiplication

factor k due to its relevant neutron absorption, it subsequently increases again due to the decay of xenon into another isotope which absorbs fewer neutrons.

The building up of reactors with solid (graphite) or liquid (heavy water) moderators is discussed, as well as other possible moderators such as light water or beryllium. In particular, the ratio is given of the absorption cross section to the scattering cross section for several moderators.

Procedures for the purification of uranium are described as well. Several methods (i.e., the exponential pile or the “shotgun” method; see Patent No. 2.969,307) are reported for testing the purity against neutron absorption of different materials. The effect of the boron and vanadium impurities in the graphite and light water in the heavy water are considered.

Different cooling systems for the reactors are considered and compared in the paper, based on the circulation of a gas (typically, air) or a liquid (light or heavy water, diphenyl, etc.).

The principles and practice for the construction, functioning and control of several kinds of reactors are reported in detail.

One reactor considered in the present paper is a low power uranium-graphite one without cooling system, where the active part consists in (small) cylinders of metallic uranium or pseudo-spheres of uranium oxide (or cylinders of U_3O_8). The control rods are made of steel with boron inserts, while limitation and safety rods are made of cadmium.

In addition, an uranium-graphite pile cooled by air or even by water or diphenyl is considered. It is pointed out that diphenyl should usually be preferred with respect to water, due to its lower absorption of neutrons and to its higher boiling temperature, but the disadvantage related to its use is mainly due to the closed pumping system required and to the possible occurrence of polymerization which makes the fluid viscous.

Another kind of reactor described in detail is made of uranium (vertical) bars immersed in heavy water. When, during the operation, the heavy water is dissociated into D_2 and O_2 , these two gaseous elements are carried by an inert gas (helium) into a recombination device. The control and safety rods are made of cadmium.

Hybrid reactors composed of different lattices in the same neutronic reactor, in order to increase the multiplication factor k , are considered as well.

A description of the possible uses of nuclear reactors, other than as power supplies, including the production of collimated beams of fast neutrons, the production of plutonium (a fissionable material usable in other reactors) or several other radioactive isotopes (for possible utilization in medicine) is as well given.

As it results clear, no published reference article behind the present paper exists. Some partial results may be found in several papers² of Volume II of Ref. [1] (see, for example, [41]), but here very many technical data and some information of historic interest (mainly on the experiments performed in order to obtain the data reported) are given.

²Just to cite some of them, we mention Ref. [14] for the use of uranium spheres or in lumps, Ref. [12] for the use of indium foils to measure slow neutron density, Ref. [20] for the introduction of danger coefficients, Ref. [24] for the methods of cooling, Ref.s [40] and [41] for the discussion about the location of uranium and control rods in the pile, Ref. [35] for the use of heavy water as moderator, and so on.

USP4 *Chain reacting system* (13 pages + 23 figures),
 by E. Fermi and M.C. Leverett,
 filed Feb. 16, 1945 (Patent No. 2,837,477; June 3, 1958).

“The present invention relates to the subject of nuclear fission and more particularly to a plant wherein the heat generated as a result of the fission process can be removed at a rapid rate and preferably in such a manner that it can be utilized for the production of power. In addition, the products resulting from the fission process in the plant can readily be removed without requiring complete dismantling of the plant.”

This paper focuses mainly on an automatic system for the control rods in a nuclear reactor (in the present case made of natural uranium and graphite) reporting, aside from several related theoretical points (already considered in previous patents), a detailed description of it. The purpose of the control circuit, ruling the position of boron or cadmium rods within the reactor, is just that of achieving a suitable neutron density to produce the desired temperature in the system.

The cooling medium is gaseous helium circulating in the active regions of the reactor, i.e. directly in contact with the uranium, where approximately the 92% of the heat is produced. The choice of such noble gas is made in order to minimize the possible corrosion of the fissile material and the absorption of neutrons, which are crucial to self-sustain the fission reaction. However, other possible choices for the coolant gas (such as air, oxygen or water vapor) are discussed as well in terms of their “danger coefficients” affecting the determination of the multiplication factor [20].

The discussion of some methods of cooling chain reacting piles was initiated in Ref. [24], but no reference published paper exists of the material presented here.

USP5 *Neutronic reactor* (8 pages + 12 figures),
 by E. Fermi,
 filed May 12, 1945 (Patent No. 2,931,762; Apr. 5, 1960).

“My invention relates to the general subject of nuclear fission and particularly to the establishment of self-sustaining neutron chain reactions, compositions of matter and methods of producing such compositions suitable for use in creating a self-sustaining chain reaction by nuclear fission of uranium by slow neutrons in a neutronic reactor.”

Particular attention is paid, in this paper, to the problem of removing heat from a chain reacting device. The system proposed (and carried into effect) is to cool the moderator (and not directly the uranium) with a liquid circulating in tubes of aluminium or some other material.

This paper is, in practice, an “evolution” of the previous patents (especially Patent No. 2,708,656) where, apart from the presentation of the novel kind of reactor mentioned above, several new physical data are presented. In particular, some details about the construction and operation of the system, including interesting tricks, are reported.

The main subject of this patent does not appear in any other published paper.

USP6 *Air cooled neutronic reactor* (11 pages + 12 figures),
by E. Fermi and L. Szilard,
filed May 29, 1945 (Patent No. 2,836,554; May 27, 1958).

“The present invention relates to a neutronic reactor which is capable of numerous uses but is particularly adapted to use for the production of the transuranic element³ ^{239}Pu and/or radioactive fission products by neutrons released during a self-sustaining nuclear chain reaction through fission of uranium with slow neutrons. More particularly, our invention relates to the removal of the heat of the neutronic reaction to such an extent that the reaction may be conducted at a more rapid rate and the production of element ^{239}Pu and/or fission products may be accelerated. Natural uranium may be used in the reaction and contain the isotopes ^{238}U and ^{235}U in the ratio of approximately 139 to 1.”

The specific reactor considered in this paper is an uranium-graphite one cooled by air, circulating within the porous graphite, and with control and safety rods made of cadmium or boron. The air serving as coolant passes only once through the reactor, so that it is not too much enriched in radioactive ^{41}Ar . Furthermore, it is exhausted at a substantial distance above ground (from the top of a stack), in order that the radioactive argon in the cooling air is sufficiently dispersed in and diluted by fresh atmospheric air before reaching any person on the ground.

Since the main object of this patent is to produce plutonium, some constructional details aimed at removing plutonium for the reactor, when a certain concentration of it is achieved, are illustrated. In particular, the mechanism for the loading or unloading of the uranium slugs is made of iron or lead in order to shield it from the radioactive bars in case they are loaded. It is also interesting to note with the authors that even after the uranium slugs have been extracted, they are so exceedingly radioactive that the produced heat would melt themselves if not immersed in water.

The production of plutonium was considered by Fermi in some previously issued reports (see, for example, Ref. [1] on pages 391 and 411), but what discussed here in so great detail (including the basic air cooling) is present in no other published paper.

USP7 *Testing material in a neutronic reactor* (8 pages + 9 figures),
by E. Fermi and H.L. Anderson,
filed Aug. 28, 1945 (Patent No. 2,768,134; Oct. 23, 1956).

“Our invention relates to the general subject of nuclear fission and more particularly to a means and method for testing materials by means of a self-sustaining nuclear chain reaction system. Such a chain reaction system may be created by the nuclear fission of uranium by thermal neutrons, utilizing natural uranium having a ^{235}U isotope content of as low as the

³That is plutonium, ^{239}Pu .

natural ratio of approximately 1/139 of ^{238}U or an enriched uranium having a higher ^{235}U content.”

The main object of this paper is to give a suitable method for determining neutron absorption by different materials, when they are irradiated with the neutrons coming from a nuclear pile. Such a reactor has deliberately a low reproduction factor, due to the apertures made in the system, from which neutrons are lost (the use of a coolant, in particular, is not provided).

The test is carried out by means of a comparison of the effects produced by the testing material with respect to those of the standard active material in the reactor. If the equilibrium position of the control rod with the test material in the reactor is further out of the reactor than it was with the standard lump in the reactor, then the test material absorbs more neutrons than the standard metal did. The opposite conclusion is, instead, reached if the control rod must be pushed further into the reactor to achieve equilibrium with the test material into the system.

Several details about the calibration of the control rod with different units are given, together with a discussion of the corrective effects due to a pressure change.

The main subject of this patent does not appear in any other published paper.

USP8 *Neutron velocity selector* (6 pages + 6 figures),
by E. Fermi,
filed Sept. 18, 1945 (Patent No. 2,524,379; Oct. 3, 1950).

“The present invention relates to neutron velocity selector apparatus and particularly to apparatus of this type which utilizes a rotating shutter.”

This paper presents a detailed description of the construction and operation of a velocity selector for neutrons with velocities up to $6000 \div 7000$ m/s. This apparatus employs a rotating shutter designed in such a way that neutrons are passed during a portion of each rotation of the shutter, the shutter blocking all neutron radiation at other times.

The selector is built up with alternate laminations of a material with high neutron capture cross section (such as, for example, cadmium, boron or gadolinium), and parallel laminations of a material with low capture probability (such as, for example, aluminium, magnesium or beryllium). This is required in order to provide a path through the shutter to the neutrons, which then pass into a ionization chamber.

The timing mechanism, adopted to activate or deactivate the neutron detection and measuring means at given times following each opening or closing of the shutter, is electronic (not mechanic), controlled by a photocell unit.

The reference published article for the main topic of the present patent is Ref. [32].

USP9 *Neutronic reactor* (5 pages + 8 figures),
by E. Fermi and L. Szilard,
filed Oct. 11, 1945 (Patent No. 2,807,581; Sept. 24, 1957).

“The present invention relates to the general subject of nuclear fission and particularly to the establishment of self-sustaining neutron chain fission reactions in systems embodying uranium having a natural isotopic content.”

This paper gives, indeed, a detailed description of a variant of the reactor presented in the previous Patent No. 2,708,656 by the same authors; it makes use of uranium arranged in plates, instead of spheres or rods. Such a different geometry is particularly efficient when a liquid moderator (for example heavy water) is used; in this case the moderator itself serves also as a coolant. In the paper, however, the use of solid moderators (like graphite or beryllium) is discussed as well.

The adoption of the given geometry leads to greater neutron losses in the reactor (due to resonant capture in uranium), but they are compensated by the mentioned use of a liquid moderator/coolant.

The main subject of this patent does not appear in any other published paper.

USP10 *Neutronic reactor* (3 pages + 4 figures),
by E. Fermi, W.H. Zinn and H.L. Anderson,
filed Oct. 11, 1945 (Patent No. 2,852,461; Sept. 16, 1958).

“This invention relates to the general subject of nuclear fission, and more particularly to a novel means for improving the establishment of self-sustaining nuclear fission chain reaction.”

An improvement of the reactors described in the previous patents, aimed at increasing the reproduction factor, is reported here, obtained by diminishing the neutron loss due to impurities within the reactor. This is achieved by encasing the reactor in a rubberized balloon cloth housing (or something like this) in order to eliminate the atmospheric air therefrom, thus eliminating both the effect of the danger coefficient of nitrogen (70% of the atmospheric air) and that of the argon present in the air, that can become radioactive. Since the removal of the air from the reactor may result in structural problems, caused by the forces brought into play by that evacuation, the reactor is then filled by a non-reactive (from a chemical and nuclear standpoint) gas such as helium or carbon dioxide.

It is also interesting to point out that the authors consider also the possibility to control (a little) the reproduction ratio of the reactor by varying the air content of it.

Just a rapid mention of the main idea of the present patent (i.e. the encasing of the pile in a balloon cloth) appeared in Ref. [25], but no detailed description of the system considered here is reported in any other published paper.

USP11 *Neutronic reactor* (3 pages + 5 figures),
by E. Fermi and W.H. Zinn,
filed Nov. 2, 1945 (Patent No. 2,714,577; Aug. 2, 1955).

“The present invention relates generally to neutronic reactors and, more particularly, to novel articles of manufacture used in and in combination with such reactors, and to the combination of such novel articles of manufacture with neutronic reactors. [...] More specifically, an object of the

present invention is to provide novel shielding means for the active portion of a neutronic reactor adapted to be used in combination therewith. Another object is to provide in a neutronic reactor a novel cooled shield. Another object is to provide a novel composite rod adapted to be used as part of the active portion of a neutronic reactor. Another object is to provide a novel rod for use as part of the active portion of a neutronic reactor which is constructed with fissionable material in a portion thereof only. Another object is to provide in a neutronic reactor novel means for introducing foreign subject matter into the active portion of the neutronic reactor for bombardment by neutrons. Another object is to provide in a neutronic reactor a novel collimated beam for utilizing the active effects of the neutronic reactor upon objects exposed exteriorly of the reactor.”

Indeed, this paper describes a series of technical improvements of a chain reacting pile, as reported above. Some attention is paid, for instance, to the shielding of the active part of the reactor, the design of the uranium-containing rods and to the recombination of D_2 and O_2 in D_2O (since heavy water is expensive).

Particularly interesting, from the scientific point of view, is the opportunity to have a well inside the active part of the reactor (which is the part most rich in neutrons and gamma rays), where objects to be bombarded with n, γ may be placed, and from which collimated beams of such particles to be used outside the reactor may be formed.

The description of the mentioned technical improvements is not reported in any other published paper (see, however, Ref. [42] for the radiation shield, Ref. [36] for the dissociation of (light) water and Ref. [31] for the collimation of a neutron beam).

USP12 *Method of testing thermal neutron fissionable material for purity* (4 pages + 4 figures),
by E. Fermi and H.L. Anderson,
filed Nov. 21, 1945 (Patent No. 2,969,307; Jan. 24, 1961).

“This invention relates to a novel method of testing the neutronic purity of uranium or other material to be used in a neutronic reactor.”

The main aim of this paper is, in fact, to outline a method for determining the “neutronic purity” (i.e., with respect to elements with an high cross section for neutron capture) of given materials to be used in a pile.

The “shotgun” test is conducted by placing an indium foil (as a neutron detector) near a neutron source, and measuring its induced radioactivity with a Geiger-Muller counter. The same measure is performed when a given quantity of boron (a standard neutron absorbing pellet) is placed near the detector foil and, subsequently, by replacing the boron with the material containing impurities. A direct comparison between the absorption caused by the unknown composition and the standard boron absorber gives the desired result for the sum of the danger coefficients of the impurities (in terms of boron equivalent).

Some theoretical developments show, as well, that the fractional absorption of the impurities with respect to uranium is approximately equal to the variation

of the reproduction factor in the pile, induced by the presence of the impurities themselves.

Neutron absorption by impurities is considered in Ref. [28] (published in 1947 but referring to work made in 1943-4), but the method adopted is completely different from that described in the present patent, which is not reported in any other published paper.

USP13 *Method of sustaining a neutronic chain reacting system* (9 pages + 16 figures),
by E. Fermi and M.C. Leverett,
filed Nov. 28, 1945 (Patent No. 2,813,070; Nov. 12, 1957).

“The present invention relates to devices of primary use for the production of neutrons by virtue of a self-sustaining chain reaction through fission of uranium or other fissionable isotopes with slow neutrons, known as neutronic reactors.”

This paper gives a general discussion of a reactor with variable critical dimensions. The pile considered is an uranium-graphite one, cooled by air and with control rods of cadmium or boron (the uranium rods are placed in aluminium jackets).

Of particular interest is the discussion of the variation of the reproduction factor k due to long and short term effects. Long term effects are, for instance, the increase of k due to the production of plutonium and its decrease due to the production of fission impurities. Instead, among the short term effects considered are the production of xenon, which absorbs neutrons, and the effect of retarded neutrons.

It is also of some relevance the pointing out that a moderator with a thickness of 1-2 feet around the uranium in the reactor acts as a reflecting screen for neutrons, with the same efficiency of an infinite thickness one. From this it follows that by using a moderator of 10 feet, for instance, the uranium content of the pile may be increased, with no relevant consequence on the efficacy of the screen.

A peculiar curiosity is the suggestion that the presence of nitrogen (as an impurity) in the reactor, which may change due to changes in the atmospheric pressure, could be used to obtain a sensitive barometer.

Some partial results may be found already in other patents and/or in several papers of Volume II of Ref. [1] (in particular, the realization of xenon poisoning is narrated on pages 428-429 of this reference). No published reference article behind the present paper exists.

USP14 *Neutronic reactor shield* (2 pages + 6 figures),
by E. Fermi and W.H. Zinn,
filed Jan. 16, 1946 (Patent No. 2,807,727; Sept. 24, 1957).

“This invention relates to radiation shielding devices and more particularly to a radiation shield that is suitable for protection of personnel from both gamma rays and neutrons.”

The mentioned shield from dangerous radiations is achieved to the best by the combined action of a neutron slowing material (a moderator) and a neutron absorbing

material. Hydrogen is particularly effective for such a shield since it is a good absorber of slow neutrons and a good moderator of fast neutrons. The neutrons slowed down by hydrogen may, then, be absorbed by other materials such as boron, cadmium, gadolinium, samarium or steel. Steel is particularly convenient for the purpose, given its effectiveness in absorbing also the gamma rays from the reactor (both primary gamma rays and secondary ones produced by the moderation of neutrons).

In particular, in the present patent a shield is described, made of alternate layers of steel and masonite (an hydrolized ligno-cellulose material).

The object of the present paper is not discussed in any other published paper.

USP15 *Method of operating a neutronic reactor* (30 pages + 42 figures),
by E. Fermi and L. Szilard,
filed Dec. 1, 1952 (Patent No. 2,798,847; July 9, 1957).

“The present invention relates to the general subject of nuclear fission and particularly to the establishment of self-sustaining neutron chain fission reaction in systems embodying uranium having a natural isotopic content.”

This paper is a later⁴ almost faithful copy of Patent No. 2,708,656, already described above. It was probably prepared (by the authors) in order to correct several misprints of the previous version. The most “relevant” change is the replacement of the 8 claims of the original mentioned patent by the following only one claim, which well summarizes the work done:

“A method of operating a neutronic reactor including an active portion having a neutron reproduction ratio substantially in excess of unity in the absence of high neutron absorbing bodies, said method comprising the steps of inserting in the active portion a shim member consisting essentially of a high neutron absorbing body in an amount to reduce the neutron reproduction ratio to a value slightly higher than unit to prevent a dangerous reactivity level, controlling the reaction by moving a control member consisting essentially of a second high neutron absorbing body inwardly and outwardly in response to variations in neutron density, to maintain the neutron reproduction ratio substantially at unity, and withdrawing successive portions of the shim member to the extent necessary to enable the reactor to be controlled by movement of the control member after the neutron reproduction value has been lowered to the point where the outward movement of the control member is insufficient to maintain the neutron reproduction ratio at the desired point, and thus to maintain the range of control effected by such movement of the control member substantially constant despite diminution of neutron reproduction ratio caused by operation of the reactor, the active portion being substantially free of high neutron absorber other than the control member and the shim member.”

3.2. Scientific reports. Here we give an account on three scientific reports from the Wattenberg archive, different from the patent papers, not comprised in the

⁴Note that the application for the present patent was filed on the tenth anniversary of the operation of the first chain reacting pile at Chicago, on December 2, 1942.

Collected Papers [1] (the first of these reports not showing the list of authors).

WAT1043v * *The Fourth Intermediate Pile* (15 pages),
Metallurgical Project,
Report C-102.

“The experiments reported here belong to a set of experiments designed to establish the arrangement of 3” cubes of alloy oxide in a graphite moderating medium which will produce the highest multiplication factor. Previous experiments were made on a simple cubic lattice of these alloy oxide cubes of such dimensions that the ratio between the volume of the graphite and the volume of the oxide was roughly 20/1. This gave a multiplication factor of 0.94. Half of the oxide cubes were then removed, leaving a face-centered lattice in which the volume ratio of graphite to oxide was 40/1. In this arrangement the multiplication factor fell to 0.86. In the present report, a body centered structure was assembled in which the volume ratio of graphite to oxide was about 10/1. It is found that the multiplication factor is again close to 0.86. From the results of these structures it is concluded that the simple cubic lattice in which the volume ratio was 20/1 represents closely the optimum conditions. Theoretical calculations support this experimental result.”

This paper did not report explicitly the list of the authors, but it was classified by Wattenberg among the Fermi papers. A careful analysis has shown that, apart from indirect information on Fermi’s activity, it was to some extent effectively written (or, at least, “inspired”) by Fermi. The date of writing was, as well, not given but, according to the material presented in the paper, it was likely written in 1942.

The results presented here, very well summarized in the abstract above, were not reported in any other published paper.

WAT1043t *Report of the Committee for the Examination of the Moore-Leverett Design of a He-Cooled Plant* (18 pages),
by E. Fermi, S.K. Allison, C. Cooper and E.P. Wigner,
Report CE-324 (1942).⁵

This report was likely written by Fermi (the chairman of the Committee) with memoranda by Allison, Cooper, Wigner, and a letter from Szilard.

In it a pile of dimensions considerably larger than that originally planned in the Moore-Leverett design is considered, this urging for a re-design of the lattice, for a reduction of the amount of uranium metal, and the consideration of the possibility to use a non cubic cell (as stated in previous conferences).

The employment of centrifugal (turbo) compressors (for the coolant) is considered, instead of reciprocating compressors, with high purity helium to avoid corrosion of uranium.

A number of technical problems, such as that of an adequate radiation shielding, the production of radioactive materials in the reactor which can be collected by

⁵This report was likely written around October 29, 1942.

helium during the shut-down of operations, or precaution on helium released in atmosphere are discussed. Problems of emergency measures for serious loss of helium and to prevent the activated uranium from melting (if the the cooling system with helium is switched off) are as well considered.

It is here pointed out that the operation of the control rods takes place by looking at the neutron density, rather than at the temperature of the reactor. Attention is also paid to possible displacements in the arrangement of the graphite due to the thermal expansion, that can cause damages to the structure and interfere with the operation of the control rods. Wigner, in particular, proposes a cylindrical arrangement instead of the spherical one.

As a conclusion, the Moore-Leverett design of a He-cooled power plant can work satisfactorily, although several details have still to be worked out.

The object of the present report is not discussed in any other published paper.

WAT149 *Measurement of the Cross Section of Boron for Thermal Neutrons* (4 pages), by E. Bragdon, E. Fermi, J. Marshall and L. Marshall, Report CP-1098 (January 11, 1944).

“Measurements of the boron cross section have been made for slow neutrons from different sources. The cross section of boron for neutrons of velocity $= 2kT/m = 2200$ meters/second at 293° K is found to be 705×10^{-24} cm²/atom. The cross section varies widely with different moderators, due to the fact that the temperature of the thermal neutrons depends on the nature of the moderator.”

As stated in the abstract, this papers deals with the measurement of the cross section of thermal neutrons on boron for different velocities of the neutrons. Velocities ranging from 1700 to 5000 m/s were obtained with a velocity selector, not described in this paper (see, however, USP8). The relevant measurements are done by varying also the pressure.

The results of the present paper converged later in the published article in Ref. [32] (see also the comment to this paper in Ref. [1], noting the different number of authors), where the velocity selector was described as well.

3.3. Notes on Meetings. A substantial part of the documents testifying for Fermi’s activity and retrieved in the Wattenberg archive consists of many notes on meetings about nuclear piles and related matters, attended by Fermi mostly in 1942. Some of these notes were already published in Ref. [1], but many of them were not included in the *Collected Papers*, probably because the corresponding material does not present itself as reports, but largely as minutes of discussions. However, these documents are of great importance both from a purely scientific point of view and for historical reasons, since all the notes but the last one (accounting for a meeting of April 1944) directly reported on the activity that lead to the achievement of the first chain reaction, ranging from May to November, 1942. In fact, although the final scientific results obtained in Chicago were later collected and discussed in subsequent papers (patents or, in few cases, published articles), the present notes testify on *how* those results were obtained and, in some cases,

also give detailed information on further, practically unknown, achievements, not reported in published papers.

Just to quote few examples, we mention an interesting trick suggested by Fermi for lowering the temperature in the pile, inspired by what happens in wind tunnels; or the control of the multiplication factor by means of the pressure of nitrogen in a liquid cooled pile. Much attention was, indeed, paid to the problem of heat transfer in the planned power and production plants, and to that of an effective and easy control of the chain reaction. Some discussions were also carried out on chain reacting piles working with fast (instead of slow) neutrons, and on different schemes for the uranium-graphite pile.

From an history of science viewpoint, these notes also present very interesting information, not available from other sources, on the Metallurgical Project, its formation and development, social and political implications (interventions of General Groves to one of the Meetings considered are registered in the corresponding notes), and so on. Several interesting and annoying discussions reveal, in fact, the urgency of the production of plutonium or other fissile material for military rather than civil applications already in 1942, the position of the problem of the moral effect of the operation and that of the relations with Army, including the issue of security and the distribution of information. However, different matters related to the physiological effect of the radiations developed in a pile (a problem raised more than once by Fermi), were considered as well, along with discussions about power utilization and long term research after the conclusion of the war.

A number of other interesting topics treated in the Meetings may be found in the detailed account of any document which follows, including (at the end) the notes on the Meeting of April 1944.

WAT1043a ◇ *Meeting of Engineering Council* (4 pages),
Present: Moore, Allison, Fermi, Leverett, Wheeler, Compton, Hilberry and Doan,
Report CE-106 (May 28, 1942).

The main discussion is on the cooling of the uranium-graphite pile by water, helium or both; some discussion is present on problems related to the pumping of the coolant. An interesting remark by Fermi is the following: since the temperature in wind tunnels is controlled by changing the cross section of the tubes, this trick can be used as well in piles for obtaining lower temperatures.

Minor discussions are on the design of a pilot power plant and a pilot extraction plant, with a remark by Fermi on the possibility of long lived activity induced in iron. Fermi also suggested a way for avoiding non uniform production of power in piles, just by blocking part of channels by graphite.

Other minor discussion is on leakage, where Fermi suggested an external graphite layer of 1 feet.

WAT1043b ◇ *Meeting of the Planning Board* (3 pages),
Present: Hilberry, Spedding, Allison, Wigner, Doan, Szilard, Wheeler, Fermi, Moore and Compton,
Reports CS-112, CS-185 (June 6, 1942).

Discussion on the status and organization of the activities: first self-sustaining pile, open pile working at a low rate of operation, helium cooling, other best cooling agents.

Re-organization of the work at Chicago (concentration of physics under Fermi), with discussion of problems on finding location, which should be chosen according to facilities and personnel at disposal (the decision, however, lies with Washington). Discussion on the steps to undertake to protect Government's position about patents and on the understanding with British (a common patent pool).

Other scientific discussions are on the purity of the graphite supplied from various factories, with a remark by Fermi on the properties of different samples. Wigner discussed the results by Creutz on resonance absorption.

WAT1043c \diamond *Meeting of the Engineering Council* (9 pages),
Present: Moore, Wilson, Seaborg, Wheeler, Leverett, Fermi, Hilberry, Compton, Spedding and Allison,
Report CS-131 (June 11, 1942).

The choice of the site location of the first pile is discussed in detail, with reference to: water power for the cooling system; alternative schemes for supplying the power needs of the plant (about 65000 kW obtained either directly from the electric lines or from boilers by using engines producing mechanical power); schedule of plants (100 W, 100 kW, 100-100000 kW, 10^6 kW); housing and list of the personnel; advantages and disadvantages of the possible association of the separation project to the atomic power project. Alternatives on the site location are Chicago or Tennessee Valley: the majority of the presents is for the first one.

WAT1043d \diamond *Meeting of the Engineering Council* (7 pages),
Present: Moore, Leverett, Fermi, Wheeler, Seaborg, Doan, Wilson and Spedding,
Report CS-135 (June 18, 1942).

Discussions on: optimum lattice constants, neutrons losses due to ducts and channels, batch versus continuous operation of the pile and relation with possible "chemical" experiments to plan (especially on the transformations undergone by U and Pu).

Fermi made some estimates on optimum lattice constants and gave relations among the multiplication factor k , the critical size and the neutron density. He favored the possibility to have more small rectangular ducts instead of less large squared ones.

Moreover, Fermi also suggests to use nitrogen as well for controlling a pile with liquid coolant, since k depends on pressure and would control up to 4% in k .

WAT1043e \diamond *Meeting of the Engineering Council* (4 pages),
Present: Moore, Leverett, Doan, Szilard, Allison, Teller, Seaborg, Wheeler, Fermi and Wilson,
Report CS-147 (June 25, 1942).

Fermi describes the advantages of the possibility to work with a pile *not* operating at optimum k .

Discussions on cooling by gas or liquid (but people later focused on the former): problems with hydrogen that reacts with uranium metal, with graphite (producing methane), etc.; problems with helium about leakage, large sound velocity (in relation to the use of blowers or compressors). The general agreement is to use helium for the 100000 kW pile.

Further discussions are on the diffusion of the fission products (in the circulating helium, the walls of the pile, etc.), with a suggestion by Fermi to not use water spray, and about blowers and compressors.

WAT1043f \diamond *Meeting of the Engineering Council* (6 pages),

Present: Fermi, Allison, Seaborg, Whitaker, Doan, Wilson, Moore, Leverett, Wheeler, Szilard, Compton, Spedding, Hilberry and Wollan,
Report CS-163 (July 2, 1942).

Discussion on the construction, installation (at Chicago) and operation of pile I, pile II and pilot plant. During the discussion on the necessary facilities, Fermi recommends to avoid limitations on water and electric supply in order not to “cut the wings”.

Several studies and possible experiments for the piles I and II are considered. Fermi proposes to: study the thermal stability in pile I or intermediate pile with heat supplied from external sources; test different cooling mechanisms on the various piles; have experiments with the piles with the precaution that the produced radioactivity does not influence them. Fermi also suggests to: measure k by using the theory of anisotropic pile or, otherwise, preferably depend altogether on theoretical calculations; design pile I for evacuation (that is: for extracting uranium oxide from the pile); etc. (gas tight, sheet metal, balloon cloth).

WAT1043g \diamond *Meeting of the Engineering Council* (4 pages),

Present: Moore, Leverett, Fermi, Wigner, Allison, Wollan, Wheeler, Seaborg, Spedding, Szilard, Steams and Wilson,
Report CS-174 (July 9, 1942).

Fermi reports on a test of chemical stability of uranium, its reaction with graphite, etc.. He also discusses a number of other topics as follows.

About the problem of heat transfer in an energy producing pile, Fermi proposes to study the behavior of the pile both when its temperature is large and when it is small, noting that the Reynolds number depends on temperature.

About the control mechanisms, he suggests an alternative scheme of control by putting in an absorbing gas, as well as to regulate the pile by raising or lowering the water level in it.

Finally, about cooling, Fermi observes that calculations are sufficient for helium but not for water, for which the intermediate experiment is required. Also, he points out that the exponential experiment is not suitable for measuring the effect of the helium diffusion through ducts.

WAT1043h \diamond *Meeting of the Technical Council* (7 pages),
 Present: Fermi, Compton, Allison, Moore, Szilard, Wigner and Wheeler,
 Report CS-184 (July 14, 1942).

Fermi discusses the use of beryllium (giving also some data) as moderator and neutron reflector, pointing out that it is not convenient to have an all-beryllium structure, but rather a pile with 2 cm of beryllium around the uranium metal, since the thermal absorption is not compensated by the $n \rightarrow 2n$ reaction.

A discussion on the shielding of experimental plant and the handling of materials (with respect to protection problems) follows, with remarks by Fermi.

About the problem of cooling, a general discussion is made on the temperature dependence of conductivity of uranium oxide and graphite. In particular, Fermi considers the possible behavior of U_3O_8 in a pile working at 100 W (corresponding to a temperature of about 1000°C), and alternative choices of cooling. For the last point, Szilard proposes the use of bismuth as coolant.

About the control system, Fermi also observes that, for proper consideration of the problem of removing oxide, it is important to decide if control columns have to take out from the pile horizontally or vertically, such a choice coming out from practical attempts (build different structures and try out).

A minor discussion on the necessity of more people involved in operations is also present.

WAT1043i \diamond *Meeting of the Engineering Council* (3 pages),
 Present: Moore, Leverett, Lewis, Fermi, Wollan, Hilberry, Whitaker, Wilson, Wheeler, Allison, Wigner, Seaborg and Doan,
 Report CE-194 (July 21, 1942).

General discussions on power plant, extraction plant (by using fluorination, precipitation with a carrier), and pile problems (radiation, recharging, breakdown, etc.) are present.

Fermi observes that it would be useful to make some of the discussed problems clear to a radiologist.

WAT1043j \diamond *Meeting of the Technical Council* (5 pages),
 Present: Fermi, Szilard, Wigner, Compton, Whitaker, Allison, Moore, Wheeler and Doan,
 Report CS-202 (July 25, 1942).

Fermi discusses the value for the multiplication factor k (equal to 1.06) obtained by using several technical solutions and with UO_2 compressed in pseudo-spheres. A general discussion on the providers of uranium metal and the product provided then follows.

Fermi raises also the question of the physiological effects of radiations, by claiming the need for a physician. On this point, Compton displays data from several medical institutions (National Cancer Institute and Chicago Tumor Institute).

- WAT1043k ◇ *Meeting of the Planning Board* (4 pages),
 Present: Spedding, Fermi, Szilard, Wigner, Doan, Moore, Wheeler, Compton and Hilberry,
 Report CS-213 (August 1, 1942).

About the problem of heat transfer and cooling, Fermi reports some values for the conductivity of the materials involved in different conditions.

A proposal comes out to study the chemistry of the pile under radiation, with Fermi observing that two tubes leading into the pile were planned for insertion of samples. Other technical topics under discussion regards the use of carbide in pilot plant, but not in experimental plant, the recommendation to use graphite around the pile (for reflecting escaping neutrons), and the problem of carbide production.

Also interesting are the discussions about the responsibility for clearance and security (leaved to Army), and the authorization for giving information about the pile to “anyone”, Conant being recognized as the final authority on the distribution of information. A mention is present about the use of the pile for power but not for production of explosives.

- WAT1043l ◇ *Meeting of the Engineering Council* (2 pages),
 Present: Moore, Leverett, Steinbach, Fermi, Spedding, Wheeler, Wigner, Seaborg and Wilson,
 Report CE-229 (August 8, 1942).

Minor discussions are present about safety and control rods, the use of a covering layer of graphite, possible external (rather than inside the pile) cooling with oil, etc..

Fermi estimates a 90% probability for achieving thermal stability in the pile.

- WAT1043m ◇ *Meeting of the Technical Council* (2 pages),
 Present: Nichols, Hilberry, Spedding, Doan, Fermi, Steinbach, Grafton, Boyd, Moore and Wheeler,
 Report CS-251 (September 4, 1942).

Fermi reports on the status of the values obtained in the multiplication factor k . Other interesting discussions regard the possible combination of water cooling and bismuth cooling (with bismuth circulating in the uranium-containing channels, between the aluminium jacket and the uranium rod), the status of production of uranium (and, in particular, about material provided by Alexander), and problems with radiation protection.

Fermi proposes to consider the possibility to test uranium metal with an exponential pile, with a remark that “the metal won’t be better than the oxide”.

- WAT1006 ◇ *Discussion of Helium Cooled Power Plant* (3 pages),
 Present: Leverett, Cooper, Moore, Wigner, Steinbach, Fermi, Szilard and Wheeler,
 Report CS-267 (September 16, 1942).

Several problems related to He cooled power plant (steel and compressors, control and safety rods, oil unaffected by radiation, etc.) are discussed in this meeting. A list of topics to be studied (and tasks to assign) is reported.

It is also interesting to point out a remark by Szilard, which argued that 10^5 kW of power were necessary to win the war.

WAT1043n \diamond *Meeting of the Technical Council* (11 pages),
Present: Compton, Wheeler, Moore, Allison, Szilard, Fermi and Spedding,
Report CS-274 (September 18, 1942).

General discussions on technical details, including a water cooled plant, are made. Quite interesting is the discussion of several points regarding the policy for the site X. These points included: triple extraction plant; water supply; association with the production unit.

It is pointed out that, while the work by Lawrence and Urey was carried out under the only control of OSRD, that performed by the Metallurgical Laboratory was under the control of OSRD through the Army. Possible alternatives were considered to propose to work not under the direct supervision of the Army, Szilard suggesting to take no action until the pile was effectively operating. Discussions about the “future” of the people working in the project are made, with particular reference to the research policy of the next 20 years.

After other discussions about alternative locations for production piles (Argonne, Tennessee, Palos Park), the attention is turned on the committee proposed by Bush for the decision about the destination of the fissile material: this had to be employed for the design and production of bombs.

Finally, the problem of further man power is discussed. Szilard recommends to associate Auger, Rasetti, Goldhaber and Rossi, taking care of an advice by Conant that the inclusion of such people in the project was possible only if the work is made in a restricted area. Another name proposed by Szilard is that of Lewis, although it is recognized that he had already too many duties, among which the development of methods for explosives in China.

WAT1043o \diamond *Meeting of the Technical Council* (8 pages),
Present: Allison, Fermi, Moore, Wigner, Compton, Wheeler and Oppenheimer,
Report CS-281 (September 29, 1942).

The main discussions deals mainly with the work related to the pile operating with fast neutrons, and the question of the move of the work to Site X (logistic problems with the Site X, etc.). To this regard, it has to be pointed out that Fermi dissented about the shift of the work on fast neutrons to Site X.

The choice of the Site X as the new main basis of the Metallurgical Project, had by now been definitive (a preliminary, rough map was also included), this having been favored to a certain extent by Army, who preferred to have all the relevant work in only one enclosure.

Other non physics arguments, touched in the meeting, are about the patent rights assignment to the American government and the collaboration of British engineers.

Instead, minor topics of scientific interest are about helium and bismuth cooled plants and water cooling.

WAT1043p \diamond *Meeting of the Technical Council* (10 pages),
Present: Allison, Fermi, Wigner, Compton, Whitaker, Moore, Cooper, Szilard, Manley, McMillan, Wheeler and Doan,
Report CS-284 (October 1, 1942).

As in the meeting of two days before, the arguments of the discussion deals with work on fast neutrons and, especially, with the move to Site X (with evaluation of alternative, possible options). The majority of the presents prefer Chicago as a suitable site in order not to waste time and, moreover, they express their preference to work not under the supervision of Army and independently of industry.

Other discussions concern the work by Fermi on slow neutrons. The development work for piles 1 and 2 was assumed to be out of way by March 1 (1943); after this was completed, the schedule comprised to work on other piles, including fast neutron pile and heavy water pile.

Mentions are made to bismuth cooling and to other technical issues.

WAT1043q \diamond *Meeting of the Technical Council* (9 pages),
Present: Allison, Fermi, Szilard, Moore, Wigner, Whitaker, Wheeler, Steinbach, Compton and Groves,
Report CS-286 (October 5, 1942).

Detailed discussions regard results about different schemes for the pile: 1) (Wigner) uranium rods, water cooling with pipes, graphite as moderator; 2) (Fermi) uranium lumps imbedded in graphite, cooling by occasional water pipes; 3) (Cooper) metal pipes, shot, and graphite as moderator, with removal of uranium metal and recharging; 4) external cooling (which gives about 300 kW power only). No definitive decision is adopted on this argument.

At a certain point of the meeting, Compton and General Groves came in reporting, quite interestingly, that War Department considered the Metallurgical Project important. The discussion then changed a little, with Allison's claims that one couldn't win the war with an externally cooled plant and Fermi's remark that the program will be delayed by several months due to change plan at the Argonne site.

WAT1043r \diamond *Meeting of the Technical Council* (9 pages),
Present: Allison, Wigner, Compton, Whitaker, Szilard, Wheeler, Fermi, Moore, Cooper, Steinbach and Kirkpatrick,
Report CS-290 (October 7, 1942).

Various arguments are treated, all related (directly or indirectly) to the move to the Site X.

Groves is said to be eager to have explosives, by June 15, 1943, several plants being assumed to be operating after June 15 (dates by Groves have not been reported in the minutes). Some discouragement in Army is reported, that the project had not achieved more so far. Moral effect of operations is discussed as well.

Technical council recommends the construction at site X of a 300 kW pile (Pile 2) by March 15 and, to this end, Fermi notes that there was no need that such a pile be made with uranium only in the form of metal.

The decision by Groves about production and extraction of fissile material at Site X is discussed, as well as concentration of the work on fast neutrons at the same site (Groves' decision urged by Oppenheimer). Topics related to power utilization and long term research (not) at the same Site X, with possible "countermeasures" to undertake regarding this last point, are also considered.

The time schedule for Pile 1 is committed to Fermi, that for Pile 2 to Whitaker, etc.. In connection to possible changes in the plans due to move of the work, Fermi notes that the original plan (for Pile 1) was to prove that chain reaction goes and to flash pile for a limited time.

A minor discussion on the question of plating uranium (and possible reactions of it) is also made.

WAT1043s \diamond *Meeting of the Technical Council* (6 pages),
Present: Allison, Szilard, Wigner, Moore, Wheeler and Fermi,
Report CS-294 (October 12, 1942)

The questions of machining graphite and sintered uranium metal are discussed in some detail.

Several options for an externally cooled pile are considered by using: 1) copper pipes; 2a) copper shell cooled by air; 2b) copper shell cooled by water spray. Fermi's preference is for choice 2a), assuming that copper didn't leak; however he himself points out that it would be difficult to find leak (then, the rubber cap method was considered). A general agreement is expressed to leave this problem to Fermi to look into.

A peculiar remark by Fermi is about his feeling that time estimates for pile to work were not certain, since the amounts of uranium metal required (to prevent loss in k) were probably underestimated. Nevertheless, he considered a mistake to wait any time at all for producing the chain reaction in this way, while he favored to put the uranium oxide in form of spheres.

Other interesting suggestions by Fermi are about the change in picture of k , and the use of a "sandwich" experiment with 4 layers of uranium metal (about 1 ton); U_3O_8 pile was suggested to be used as a standard, and a gain of 0.8% in k was estimated just by removing nitrogen.

More discussions are again about the move to Site X: people felt not to transfer until the working situation was not clear. Fermi observes that all matter about Site X appeared to arise from a mistaken impression that experimental work was practically finished.

WAT1008 \diamond *Conference on Lattice Spacing* (2 pages),
Present: Steinbach, Leverett, Fermi, Wigner and Wheeler,
Memo #15 (October 21, 1942).

Estimates about optimum lattice spacing in the pile and C/U ratio for the helium cooled plant are presented, by taking into account the request of a minimum

total amount of uranium metal. Fermi suggests to save the amount of metal by diminishing the proportion of U to C toward the outside of the pile.

WAT1043u \diamond *Meeting of the Technical Council* (4 pages),
Present: Allison, Compton, Fermi, Moore, Spedding, Szilard and Wigner,
Report CS-356 (November 19, 1942).

Preliminary agreements are discussed in this meeting about the preparation of a report for a committee (which included industrial specialists on production problems) formed for examining the Metallurgical project in Chicago (alternative to the project based at Berkeley), that will come on November 26. The topics discussed regard the purity of the final product (plutonium), its radioactivity, spontaneous heating, etc., by pointing out that very little was known about the metallurgy of plutonium, and the processes proposed for producing it seemed very far from industrial possibilities.

Remarks are present about the availability in U.S.A. of 1000 tons of uranium, and that no slowing down of neutrons would be required for Piles 1 and 2, although Wigner pointed out that studies on fast neutron reactions were still preliminary.

About non strictly scientific issues, it is quite interesting to note the invitation from Washington authorities to go ahead with the production of plutonium, and the remark on General Groves who was interested in all possible military uses of what studied in Chicago, rather than applications to power production.

In these notes it is pointed out that a report on the chain reaction of about 10 pages should have been prepared by Fermi (along with the contributions of other scientists on other subjects), this report being unknown.

WAT \diamond *Notes on Meeting of April 26-28, 1944* (5+8 pages),
Present: Fermi, Allison, Wigner, Smyth, Szilard, Morrison, Watson, Feld,
Hogness, Young, Weinberg, Creutz, Cooper, Vernon and Ohlinger,
Report N-1729, Eck-209.

This report is composed of two papers accounting for a two-day meeting (April 26-28, 1944).

A large part of the first paper, with much of the Fermi's intervention at the two-day meeting, was already published in the *Collected Papers* [34]. There, the discussion focused on chain reaction for the production of a power of about 10^6 kW. A large mother plant was conceived for producing plutonium to be used as fissile material in smaller plants; Fermi noted that this arrangement could be useful for the heating of towns. Then, after a brief theoretical discussion, with numerical estimates and data, for the full metal utilization, Fermi focused on four different types of piles, both operating with slow neutrons and fast neutrons, and depending on the percentage of the enrichment of the fissile material and the moderator employed. The remaining part of the first paper, not published in [34], dealt with alternatives to what discussed by Fermi proposed by Szilard, coming out by "assuming more optimistic values of the constants so as to indicate other potentialities".

The second paper dealt mainly with a discussion by Morrison on several scientific, economic, and social issues related to pile producing power, resulting quite interesting from an historical point of view. Among the remarks to the Morrison's relation,

we mention that “Fermi questioned the estimated value of [the number of neutrons produced/number of fissionable atoms used up] = 2.5 on the ground that it might be too optimistic and pointed out that there is a long range future in developing the full utilization of [^{238}U] and thorium”.

3.4. Edited reports. In the Wattenberg archive several reports are present, describing some of the work performed in 1943 and 1944 by the division of the Metallurgical Laboratory headed by Fermi. As it is already known (see, for example, Ref. [2] or the introduction to the papers of Volume II of Ref. [1]), Fermi played a very active role in the work officially assigned to others, so that although none of these reports describes (theoretical or experimental) activities directly performed by him, they nevertheless reveal precious information about part of the work done under the supervision of Fermi. Of course, these few reports account only for activities not directly related to military applications, although they were finalized primarily to the production of fissile material for explosives.

The detailed description of the four reports available follows below.

WAT1023 * *Report for Month Ending September 25, 1943* (55 pages),
 edited by A.H. Compton, S.E. Allison and E. Fermi,
 Report CP-964.

This report does not contain the description of the work performed directly by Fermi, but rather it describes some of the activities performed in the month of September 1943 by different people under Fermi’s supervision.⁶ The most interesting ones are summarized below.

Much work, both experimental and theoretical, was devoted to the study of a so called P-9 pile, that is a chain reacting system with heavy water as a coolant. The Zinn group was involved in making plans for an experimental P-9 plant at Argonne, while the Young group worked on the design of a P-9 pile, both for a heterogeneous and a homogeneous pile. In a P-9 pile more fissile material had to be used for several technical reasons (related to pumps and heat exchangers employed), but this was compensated by a higher value of the effective multiplication factor k . Other problems to be solved were that of the separation of the uranium oxide from the circulating heavy water and the method to choose for separating the heavy water from the cooling liquid (in order to use it again after a given cycle), the determination of the critical size for a P-9 pile, etc.. A sketch showing one possible arrangement for a (near) homogeneous P-9 slurry pile was presented as well.

Another research conducted by some people of the Zinn group regarded the “cell saturation” effect, induced by increasing the absorption cross section of a single cell (to be used in the lattice of a pile) to such an extent that the change in reactivity of the pile was no longer proportional to the amount of impurity added, but rather to its square.

The group headed by Anderson studied, among the other things, the residual radioactivity of control rods made of different materials, the effect of fast fission on the multiplication factor, and remeasured the ratio of the absorption cross sections

⁶In this report, the summary of these activities was written (on September 27, 1943) by Wigner “in the absence of Mr. Fermi”.

of boron and hydrogen.

Marshall, instead, studied and prepared a velocity selector consisting of a sandwich of aluminium and cadmium sheets for obtaining measurements on neutrons with definite energy (see previous section), while Morrison performed an experimental study on the boundary conditions for the neutron density between paraffin and graphite for a study on a neutron reflector, with the determination of the temperature effect on the diffusion length in graphite.

The Feld group got involved in the investigation on inelastic cross sections of several heavy elements (lead, bismuth, iron and uranium), which were relevant for fast neutron chain reaction, while started novel measurements on the $(n,2n)$ and (γ,n) reactions on beryllium with the paraffin pile technique.

In this report, a large account is also given to some theoretical activity performed by several people, as emphasized by Wigner himself: “the Theoretical Physics Section’s report for this month is in considerably more detail than was the custom in previous months”. Then Wigner interestingly continues: “It is not expected to report in similar detail in the future, as a good part of the work done by us is principally for our own use. However, it was intended to give a more adequate picture of the work that we are doing”.

As already mentioned, much of the theoretical work was devoted to the P-9 pile, but another interesting investigation (by some people of the Weinberg group) dealt instead with the fast chain reacting pile, having found that the measured cross section for fast fission was smaller than previously assumed (the ratio of the fast fission neutrons to the thermal fission ones was previously measured incorrectly).

Other researches regarded the study of possible danger situations in which control rods could not be governed due to a pressure damping in the cooling circuit, or the studies on the preferred geometrical form of a pile, its dimensions or other technical details (pumps, valves, heat exchangers, etc.)

WAT1027 * *Report for Month Ending December 25, 1943 - Part II* (6 pages),
edited by A.H. Compton, S.E. Allison and E. Fermi,
Report CN-1190.

This report does not contain the description of the work performed directly by Fermi, but rather it describes some of the activities performed in the month of December 1943 by different people under Fermi’s supervision. The summary of the first part of this report is in Ref. [43], while the second part dealing with the work performed by the Anderson group is considered here.

The Anderson group determined the yield of plutonium per kWh for the Argonne pile, and predicted that the Hanford 250 kW operations should produce about 230 grams of plutonium per day. They also studied neutron yields from polonium by irradiating different samples (lithium sulphur, chlorine and argon) with alpha particles.

WAT1037 * *Report for Month Ending August 26, 1944* (38 pages),
edited by A.H. Compton, E. Fermi and W.H. Zinn,
Report CP-2081.

This report does not contain the description of the work performed directly by Fermi, but rather it describes some of the activities performed in the month of August 1944 by different people under Fermi's supervision. The most interesting ones are summarized below. It was here noted that the Chicago Pile N.3 completed its second month of operation, while a silver tape recorder was completed and installed on CP-2.

The Seren group studied the properties of the thermal column (see the previous section), while Zinn performed measurements on the Bragg reflection of a highly collimated beam of thermal neutrons and, more in general, on neutron spectroscopy. Lichtenberger studied, instead, the scattering from strong absorbers, Morrison and Teller having identified the isotope ^{112}Cd as that responsible for the strong capture of thermal neutrons, while Wattenberg prepared photo-neutron sources made by activation of several nuclides.

Finally, Anderson focused on the neutrons from the reaction $^3\text{H} + ^2\text{D} \rightarrow ^4\text{He} + \text{n}$ and, in general, studied possible transformations of thermal into fast neutrons, while the Nagle's group measured the yield of delayed neutrons.

WAT1039 * *Report for Month Ending October 28, 1944* (27 pages),
edited by A.H. Compton, E. Fermi and W.H. Zinn,
Report CP-2301.

This report does not contain the description of the work performed directly by Fermi, but rather it describes some of the activities performed in the month of October 1944 by different people under Fermi's supervision. The most interesting ones are summarized below.

The group guided by Zinn studied the poisoning of the chain reaction by ^{135}Xe in CP-3 (see the previous section) and related arguments, and May and Anderson measured the nuclear constants of ^{233}U , whose behavior they found similar to that of ^{235}U but giving larger values for k , so that the use of ^{233}U was suggested to be more favorable than that of Pu.

Langsdorf studied, instead, the resonance scattering of neutrons, while the Seren group measured the activation cross section of columbium Cb, which resulted to be a useful information for producing stainless alloy with uranium.

WAT1040 * *Report for Month Ending November 25, 1944* (24 pages),
edited by A.H. Compton, E. Fermi and W.H. Zinn,
Report CP-2436.

This report does not contain the description of the work performed directly by Fermi, but rather it describes some of the activities performed by different people under Fermi's supervision. The most interesting ones are summarized below.

The Zinn group continued their studies on the Bragg reflection of thermal neutrons from a crystal (considered as a neutron spectrometer), and observed also the total reflection by Cu, Al, Be, glass and graphite mirrors.

The Lichtenberger group, instead, made boron absorption measurements in order to study the variation with energy of the resonance absorption of ^{238}U , while the Wattenberg group mainly focused on photo-neutrons from U+Be sources.

Finally, the Hill group studied the tuning of coincidences in α -chambers and made

an analysis of a number of pictures from cloud chambers searching for ternary fissions (and possible appearance of three-particle fissions).

3.5. Lecture Notes. Once the pile program of the Metallurgical Project in Chicago was sufficiently advanced not to need a continuous attention by Fermi, he definitively moved to Los Alamos (in September 1944) to join the Manhattan Project. Here Fermi began to give isolated lectures on many different subjects [5, 2], related to that project, for the benefit of the people who worked at Los Alamos, many of them being just students or graduated guys. Then, after the end of the war, in the Fall of 1945 he taught a regular course on neutron physics to about thirty students: this was the first time that such a complete course was given, ranging over more than ten years of important discoveries, and also the first occasion for the scientists who contributed in those achievements to pause and reason a bit more on the results obtained.

We know about the content of this course from the notes taken down in class by one of the attending students, I. Halpern, who assembled them into a (classified) typescript on February 5, 1946. A first part of the Fermi lectures at Los Alamos, containing neutron physics without reference to chain reactions, was declassified on September 5, 1946, while the remaining part has been declassified only in 1962. Both parts have been later published in the *Collected Papers* by Fermi [38]. Leaving aside the pregnant didactic style by Fermi, the main relevance of such notes is, as we have already mentioned, that they present for the first time a complete and accurate treatment of neutron physics from its beginning, including a detailed study of the physics of the atomic piles. In this respect it is not surprising that especially the second part of the notes, dealing just with chain reactions and pile physics, was considered as “confidential” material by governmental offices.

However, we have recently recovered a *different* version of the Fermi lectures at Los Alamos, formerly belonged to James Chadwick and now deposited at the Churchill Archive Centre in Cambridge (U.K.). The folders relevant to us are essentially two. The first one (CHAD I 17/3) contains a letter from R.T. Batson of the Atomic Energy Commission (A.E.C.), a copy of the paper *Elementary Theory of the Pile* by Fermi⁷ and a copy of only the *first part* of the Halpern notes of the Fermi lectures. The second folder (CHAD I 4/1) contains a version of the *complete* set of lectures made by A.P. French, dated June 23, 1947.

It is apparently not strange that the material of the first folder belonged to Chadwick, since he was the respected (also by Americans) leader of the British Mission in the United States. The biggest part of the British contingent was, in fact, at Los Alamos, and Chadwick himself was present at the world’s first nuclear test at Alamogordo on July 16, 1945. Several scientists of the British Mission were very young and, among the others, it was Anthony P. French who graduated in Physics at the Cambridge University just in 1942. In the same year he joined the atomic bomb project (“Tube Alloys”) at the Cavendish Laboratory, and was later sent to Los Alamos in October 1944 as a member of the British Mission. Here he worked with E. Bretscher, O.R. Frisch, J. Hughes, D.G. Marshall, P.B. Moon, M.J. Poole, J. Rotblat, E.W. Titterton and J.L. Tuck in the field of experimental nuclear

⁷This paper is reproduced in Ref. [1]; in particular see page 538 of Volume II.

physics [44],⁸ and returned to the United Kingdom in 1946, working for two years at the just newly formed Atomic Energy Research Establishment (A.E.R.E.). The second folder of the Chadwick papers mentioned above contains just the notes of Fermi course on neutron physics taken by French on his own, when he was at Los Alamos, and later (1947) re-organized into a final version when he came back to England.

The present recovery thus shows a clear historical and scientific relevance. However, while the historical interest is the main subject of a different paper [45], we here focus only on the scientific relevance of that recovery, which is clearly centered about the fact that our previous knowledge of the Fermi course was incomplete and, to some extent (limited to the Halpern notes) misleading. As his usual, Fermi was very accurate in the choice of the topics, that he developed in detail and in a very clear manner, a peculiarity which does not often emerge from the notes taken directly down in class by students, and later arranged into the Halpern version.

We have performed a careful analysis of the mentioned documents, whose main results are summarized below. First of all, our study has shown that the French notes do *not* depend on the Halpern ones, but French probably saw them (the organization of the introduction is similar). The topics covered are exactly the same, although to a certain (minor) extent the material is organized in a little different manner. The detailed table of contents (including sections and subsections) follows.

CHAD * *Neutron Physics. A Course of Lectures by E. Fermi* (113+iii pages),
Notes by A.P. French (June 23, 1947).

1. Sources of neutrons
 - Natural Sources
 - (a) Alpha particle sources
 - (b) Photo-neutron sources
 - Artificial Sources
2. The Isotopic Chart: Nuclear Masses and Energies
 - The Isotopic Chart
 - Energy Balance of Reactions
 - The Binding Energies of Nuclei
 - The Packing Fraction Curve
3. The Scattering of Neutrons (Part 1)
 - General Considerations
 - Elementary Theoretical Treatment
 - 1) Elastic Scattering
 - 2) Inelastic (n, n) scattering
 - 3) Inelastic (n, m) scattering
 - 4) Inelastic (n, γ) scattering
4. Resonance: Models of the Nucleus
 - Resonance in Nuclear Reactions
 - Two Models of the Nucleus
5. The Scattering of Neutrons (Part 2)
 - The Solution of Schrodinger's Equation

⁸The remaining part of the British Mission was composed by B. Davison, K. Fuchs, D.J. Littler, W.G. Marley, R.E. Peierls, W.G. Penney, G. Placzek, H. Sheard and T.H.R. Skyrmes.

- The Scattering Cross Section
- Neutron-Proton Scattering
- The Breit-Wigner Formula
- The Effect of Chemical Binding on Scattering
- Scattering Cross Sections for Other Elements
- 6. Slow Neutrons as Waves
 - Introduction
 - Isotopic Effects
 - Penetration of Thermal Neutrons
 - The Production of Very Slow Neutrons
 - Reflection and Refraction
- 7. The Slowing Down of Neutrons
 - Introduction
 - The Energy Loss in One Collision
 - Many Collisions
 - The Spatial Distribution of Slowed Neutrons
 - Theory of the Spatial Distribution
- 8. The Age Equation
 - Derivation of the Age Equation
 - 1) Diffusion
 - 2) Energy Drift
 - The Problem of Point Source
- 9. Thermal Neutron Distribution
 - The Basic Equation
 - Point Sources of Slow Neutrons
 - Point Sources of Fast Neutrons
 - Bounded Media
 - The Measurement of Diffusion Length
 - Diffusion in Graphite
 - Some Useful Quantities and Relationships
- 10. The Reflection of Neutrons
 - Introductions
 - Approximate Solution of the Escape Problem
 - Exact Solution by the Integral Equation Method
 - The Albedo
 - Measurement of the Albedo
- 11. The Stability of Nuclei
 - The Binding Energy of a Nucleus
 - 1) The Liquid Drop Model
 - 2) Nuclear Composition
 - 3) Coulomb Forces
 - 4) The Odd-Even Effect
 - Determination of Coefficients
 - The Binding of Neutrons in Nuclei
- 12. Nuclear Fission
 - The Possibility of Fission
 - Limitations on the Occurrence of Fission
 - The Liquid Drop Model in Fission

- The Particles of Fission
- Cross Section for Fission and Other Processes
- 13. The Possibility of a Chain Reaction
 - The Properties of Natural Uranium
 - 1) The High Energy Region
 - 2) The Thermal Region
 - Moderators
 - Homogeneous and Lumped Graphite Piles
 - The Possibility of a Homogeneous Pile
- 14. The Heterogeneous Pile
 - The Design of a Lumped Pile
 - The Determination of Pile Constants
 - 1) The Magnitude of ϵ
 - 2) $(1 - f_R)$
 - 3) Calculation of f_T
 - Reproduction Factor and Critical Size
- 15. The Time Dependence of a Pile
 - The Time-Dependent Equation
 - Evaluation of the Period
- 16. Practical Aspects of Pile Physics
 - The Determination of k
 - The Study of Pile Materials
 - Energy and Radiation Production
 - Shielding
 - Other Types of Pile
- 17. Fast Reactors
 - Elementary Considerations
 - The Integral Equation to the Neutron Distribution
 - The Critical Size for a Fast Reactor
 - Supercritical Reactors

Problems and Exercises

Almost all the topics listed above were expounded by Fermi; according to French, when Fermi was absent, R.F. Christy and E. Segrè treated the scattering of neutrons and the albedo in the reflection of neutrons, respectively.

The text of the notes is different in the French and Halpern versions; in few cases, however, similar or even identical words or sentences are present in both versions, likely denoting quotes from an original wording by Fermi. In general, the French notes are much more detailed and accurate (as may be roughly deduced even looking at the table of contents reported above), with a great number of shorter or larger peculiar additions⁹ (explanations, calculations, data or other, and 5 more exercises) not present in the Halpern notes. It is quite interesting that the

⁹The case is completely different, for example, from that of the revision of the (first part of the) Halpern notes made by J.G. Beckerley in 1951 (document AECD 2664 of the Atomic Energy Commission). Here the author *re-wrote* the Fermi lectures by including several additions from *other* sources, “where clarity demanded more information and where the addition of recent data made the text more complete.” Contrarily to the present case (as it is evident from the text of the notes), Beckerley “was not privileged to attend the course” by Fermi.

greater detail already present in the French notes increases even more in quality (especially figures and data) in the last part, directly related to chain reactions and their applications, and, moreover, explicit references to bomb applications are made (see below). By limiting ourselves to significative scientific remarks or discussions, the French version of the Fermi lecture notes contains about 100 additions, 18 of them being quite relevant while the remaining part accounts for minor remarks, calculation details or figures. Instead the peculiar additions present in the Halpern version but not in the French one are only about 30 (and 3 more exercises), only one of them being relevant. Also, the French paper contains the six questions which were set as a final examination at the end of the lecture course.

The most relevant additions deals with the following (the page number refers to that present in the French manuscript):

- (French, page 6) the entire section *The Binding Energies of Nuclei*, where the definition of the binding energy and an example for calculating it in a specific case is reported;
- (French, page 19) the introduction of the first section of chapter 5: “In this section we consider the solution by wave mechanics of a simple problem in nuclear scattering. The nucleus is considered as a centre of force, the force being of short range, so that it ceases to exist beyond a certain distance r_0 from the origin. The actual shape of the nuclear potential then approximates to a square well, as shown in Fig. 14. The potential U is negative and constant over most of the nucleus. This corresponds to the facts, as far as we know them, of the interaction between a neutron and a nucleus. The depth of the nuclear potential well is equal to the binding energy, that is about 8 MeV”;
- (French, page 27) some details about the Bragg scattering of slow neutrons by an element with different isotopic composition, ending with the following remark: “the total scattering intensity is thus given by $I_{sc} = \text{const.} (\sigma_1 + \sigma_2 \pm \sqrt{\sigma_1 \sigma_2})$, and may be seen to consist of coherent and incoherent contributions, the latter not being subject to interference”;
- (French, pages 35-36) a long discussion, with detailed calculations about the spatial distribution of slowed neutrons, aimed at calculating the source strength in neutrons per second both for a thermal detector and for a resonance detector (final explicit expressions are reported);
- (French, page 42) calculation details about the neutron scattering in a medium (with the determination of the mean free path), ending with a prediction for the neutron-proton scattering cross section (in water) of $\sigma \simeq 20$ barns which “agrees very closely with the accepted value”;
- (French, pages 52-53) discussion on calculation details aimed at solving the so-called (Fermi) age equation for the diffusion of neutrons from a Ra-Be source in a column of graphite of square section (with length of side a) and infinite length; the effective length of a side of the column, $a = a_{\text{geometrical}} + 2 \cdot (0.67 \lambda)$ (λ being the mean free path), and the range of the neutrons, $r_0 = \sqrt{4\tau}$ (τ being the age parameter), are introduced; the numerical values of r_0 (instead of only τ as in the Halpern notes) for three (instead of two) typical neutron energies are given; the addition in the French notes ends with the peculiar observation that “we have the somewhat paradoxical result that the system can be made infinite for fast neutrons being slowed down, but not for the same neutrons when they have become thermal”;

- (French, pages 59-60) after some calculations, the section on the measurement of the albedo ends with the observation that “a thermal neutron in these media [paraffin and water] makes about 100 collisions before being captured. The distance it travels, measured along the path, is about 80 cm on the average, and the time it takes to do this, which is its lifetime as a thermal neutron, is something less than a millisecond”;
- (French, page 61) introductory remarks on the binding energy of a nucleus, with the theoretical expression for the measured mass of an atom in terms of A , Z and the said binding energy;
- (French, pages 63-65) several important additions related to the stability of nuclei (according to the even- and odd-ness of Z , A or both) and the accurate determination of the expression of the binding energy of nuclei in terms of Z and A , with several numerical data (and a graph);
- (French, pages 72-73) the inclusion of three graphs for the cross section of (n, γ) and $(n, \text{fission})$ processes on uranium as function of the incident neutron energy;
- (French, pages 79-80) relevant additions about homogeneous and lumped graphite piles: explicit calculations of the neutron absorption volume by uranium spheres of 3 cm radius (and of other quantities) lead to the conclusion that “no homogeneous pile of this type will work, and we must therefore devote our attention (if we are considering only the U-graphite combination) to heterogeneous piles”;
- (French, page 81) small introduction (with key comments) to the design of a lumped pile, with figures of lattice structures with spherical lumps or rods of uranium;
- (French, page 84) two relevant figures (and related discussion) about efficient cooling systems (by blast of air or water flowing) for piles; introductory remarks to the section dealing with the reproduction factor and critical size of a pile, with a graph of the actual neutron density in a finite pile as a function of the distance from the center of the pile;
- (French, pages 86-87) explicit expressions and related comments on the reproduction factor k as a function of geometrical and other parameters of the pile;
- (French, pages 99-100) “We have discussed the mechanism of thermal neutron chain reactions. The question now arises how to produce a nuclear explosion”; introductory remarks about fast reactors starting from the calculated expression for the growth of neutron density in a reactor;
- (French, pages 100-101) definition, calculations and related discussion on the transport cross section and transport mean free path for neutrons in a fast reactor with a core of ^{235}U and a tamper (neutron reflector);
- (French, pages 103-104) discussion of equilibrium conditions (with explicit expressions) for a fast reactor and mathematical expressions for some quantities describing neutron losses;
- (French, page 110) the end of the chapter on fast reactors (and, then, of the lecture notes) is: “in this way one can calculate the e-folding time for a fast reactor, and its value thus found will be valid until mechanical effects set in – these having to be known before the efficiency etc. of the bomb can be estimated”.

The only relevant addition in the Halpern version is, instead:

- the description of a fast neutron detector, based on the scattering of a neutron flux by a paraffin layer (see page 471 of Volume II of Ref. [1]).

3.6. Other contributions. Few other minor documents, of different nature and relevance, have come to light during our research.

Although not properly a paper or a report, the first document we point out here is a letter written by Fermi to Lord Rutherford as early as in 1934, when he and his group in Rome started to study the radioactivity induced by neutron bombardment. As recalled above, these studies led, in October 1934, to the discovery of the important properties of slow neutrons (see Patent USP1). This document is presently conserved among the Rutherford Papers at the Cambridge University Library (U.K.). The text of the letter is as follows:

Rome, June 15th, 1934

My dear Prof. Rutherford,

I enclose a reprint of a paper on the present status of our researches on the activation of uranium. The same results shall appear shortly in *Nature*.

We have been forced to publish these results of a research which is actually not yet finished by the fact that the newspapers have published so many phantastic [sic!] statements about our work that we found it necessary to state clearly our point of view.

We are now engaged in trying to understand the influence of the neutron energy on the activation of elements. We try to do this using neutrons from a source of Em+B .

We are interested in this problem not only as it can throw some light on the processes involved, but also because we plan to construct a neutron tube similar to that of the Cavendish laboratory.

In this connection I would be much obliged if in case you have tested your tube for activating elements, you would let me know some data on the intensities of the activations.

The construction of this tube would be much facilitated for us if it were possible for some assistants of our laboratory (Drs. Amaldi and Segré) to come this summer to the Cavendish Laboratory in order to see the apparatus and possibly be instructed about its use.

I would be very grateful to you if you will give me an answer on this point.

With kindest regards

yours very truly

Enrico Fermi

Here, the relevant information, mainly from an historical point of view, is the reference to the construction of “a neutron tube similar to that of the Cavendish laboratory” and, particularly, the request by Fermi of “some data on the intensities of the activations” ought to be obtained by the Rutherford group at the Cavendish Laboratory. Indeed, this testify for an attempt made by Fermi to set up some

collaboration among the two groups even *before* that Amaldi and Segrè came to Cambridge in the summer of 1934. Although four letters by Rutherford to Fermi were known (they are conserved at the Domus Galilaeana in Pisa, Italy), such collaboration at a distance had not been addressed previously. The reply to the letter by Fermi is, indeed, known¹⁰, but this fact cannot be deduced from it. The answer by Rutherford to the specific request by Fermi was negative, denoting the advantage of the Rome group over that of the Cavendish Laboratory on this point (probably unexpected by Fermi): “I cannot at the moment give you definite statement as to the output of the neutrons from our tube but it should be of the same order as from an Em+Be tube containing 100 millicurie and may be pushed much higher.”

The second document we consider here is the following:

Total Collision Cross Section of Negative Pions on Protons,
by D.E. Nagle, H.L. Anderson, E. Fermi, E.A. Long and R.L. Martin,
Phys. Rev. **86**, 603 (1952).

“The transmission of negative pions in liquid hydrogen has been measured using the pion beams of the Chicago synchrocyclotron. Pion beams with energies from 60 to 230 MeV were used. The transmissions were measured using scintillation counting techniques. The total collision cross section increases with energy starting from small values at 30 MeV and rising to the “geometrical” value of about $60 \times 10^{-27} \text{ cm}^2$ at about 160 MeV. Thereafter up to 220 MeV, the cross section remains close to this value. The steep energy dependence at low energies is consistent with interpretation that the pion is pseudoscalar with a pseudovector interaction.”

As the companion paper in Ref. [46], it was presented at the 1952 Annual Meeting of the American Physical Society held at New York on January 31 - February 2, 1952; in the mentioned journal, only the abstract of both papers were reported, as custom for the proceedings of that meeting. It testifies for some of the work performed at Chicago by Fermi and his collaborator on pion physics [47]; the results are summarized in the abstract reported entirely above. Strange enough, the paper considered does not appear among the *Collected Papers* [1], contrary to what happen for the paper in [46], although both abstracts were published in the journal on the same page.

The last document is a popular article written by Fermi for a newspaper¹¹, in the occasion of the tenth anniversary of the operation of the first chain reacting pile at Chicago, on December 2, 1942:

Fermi's own story,
by E. Fermi,
Chicago Sun-Times, November 23, 1952.

¹⁰It is reported by E. Amaldi in his not very known paper *Neutron Work in Rome in 1934-36 and the Discovery of Uranium Fission*, Riv. Stor. Sci. **1**, 1-24 (1984).

¹¹Although this paper was effectively published, again it was not included among the *Collected Papers*, so that it is practically unknown.

Here Fermi gave a personal description of that event, preceded by a short story of the main stepping-stones that led to the realization of the first chain reaction, starting from the discovery of radioactivity by H.A. Becquerel. It is particularly interesting the conclusion of this article, where Fermi stated his view (and hope) about science and possible military applications of it:

The further development of atomic energy during the next three years of the war was, of course, focused on the main objective of producing an effective weapon.

At the same time we all hoped that with the end of the war emphasis would be shifted decidedly from the weapon to the peaceful aspects of atomic energy.

We hoped that perhaps the building of power plants, production of radioactive elements for science and medicine would become the paramount objectives.

Unfortunately, the end of the war did not bring brotherly love among nations. The fabrication of weapons still is and must be the primary concern of the Atomic Energy Commission.

Secrecy that we thought was an unwelcome necessity of the war still appears to be an unwelcome necessity. The peaceful objectives must come second, although very considerable progress has been made also along those lines.

The problems posed by the world situation are not for the scientist alone but for all people to resolve. Perhaps a time will come when all scientific and technical progress will be hailed for the advantages that it may bring to man, and never feared on account of its destructive possibilities.

4. CONCLUSIONS

In the present paper we have given a detailed account of the many documents recently retrieved, and mainly testifying Fermi's activity in the 1940s about pile physics and engineering. These documents include patents, reports, notes on scientific and technical meetings and other papers; all of them have been carefully described, pointing out the relevance of the given paper for its scientific or even historical content.

From a purely scientific point of view, the patents on nuclear reactors, some reports or notes, and the complete set of lecture notes for a course on neutron physics are the most important documents. Quite intriguing are the papers written for the patents issued at the U.S. Patent Office, since they directly deal with the technical and operative construction of the nuclear reactors. Although the activity by Fermi on this was early well recognized from the accounts given by the living testimonies and partially documented by several papers appeared in the Fermi's *Collected Papers* (published in the 1960s), as it is evident from what discussed above, from the newly retrieved papers a number of important scientific and technical points come out, putting a truly new light on the Fermi's activity in the project. In few words, at last we can recognize exactly what Fermi *effectively* did for the success of the pile project, since it is now well documented.

The other papers, especially the notes on meeting, are also of particular relevance for the history of the achievement of the knowledge on chain reactions (with particular reference to the construction of the first chain reacting pile in Chicago at the end of 1942) and its application in the Manhattan Project. In some documents, explicit references to weapons, their use during the Second World War, and related matters appear. Quite a persistent “obsession”, even as early as in 1942, for the production of fissile material (mainly plutonium) for military uses emerges from many documents, a feature which was not at all considered in previous historical reconstructions. The attitude of Fermi on this point comes out very clear: he is not “obsessed” at all by military applications (like, instead, several other colleagues), but rather by civil use of nuclear energy (for “the heating of towns”) and, quite unexpectedly, by the physiological effects of radiations. Quite important (and, again, unexpected) are, as well, the discussions at several meeting of long term physics research and post-war research policy, and those regarding the relationship, about nuclear power for pacific and/or military use, between U.S. and Britain just after the end of the war.

Although we have discussed in some a great detail all of the novel documents, given their obvious relevance, we can expect that accurate studies on them, to be performed in order to explore the full implications of them, have still to come, probably committing the people interested in scientific and historical matters for some time in the near future.

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APPENDIX A. ENRICO FERMI'S PAPERS

In the following we report the complete list of works by Enrico Fermi, as recognized on January 2008. This list is probably incomplete; a number of papers issued in U.S.A during the Second World War, for example, have been treated as restricted data for some time by the competent governmental authorities.

In this list we have included also papers not directly written by Fermi, but directly related to works performed by him, such as lecture notes, reports or notes on meetings, and so on. These papers have been pointed out by special symbols. In particular, we have denoted with a \diamond those where the contribution by Fermi is explicitly recognizable (typically, notes on meetings), and with a * those where such contribution can be deduced only indirectly (lecture notes or edited reports).

The following list has been compiled by adopting a full chronological criterion. We have ordered the papers according to: 1) the explicit date reported in it; 2) the date of reception of the paper by the publishing house; 3) the publication date. If none of this applies, we have made recourse to some internal analysis of the given paper and to the comparison with other papers, also taking into account (if possible) the ordering of the Enrico Fermi's *Collected Papers* (FNM) prepared by E. Segrè et al. (which, however, is not strictly chronological).

The papers already present in the *Collected Papers* have been pointed out by the code FNM followed (if applicable) by the related list number. Those unpublished present only (for what we know) in the Wattenberg Archive have been denoted by the code WAT followed (if applicable) by the list number of that archive. Finally, the patents registered at the U.S. Patent Office have been pointed out by the code USP followed by the chronological list number.

For books, we have reported only the first, original edition of them, omitting the subsequent translations.

Books

- Book1 *Lezioni di elettrodinamica*, pubblicate a cura dello studente Adelino Morelli, pp. 95, Stabilimento tipo-litografico del Genio Civile, Roma, [s.d.].
- Book2 *Lezioni di Fisica teorica*, dettate dal Prof. E. Fermi, raccolte dai Dott. Dei e Martinozzi, pp. 60, [s.n.], Roma, 1927.
- Book3 *Introduzione alla fisica atomica*, pp. 330 Zanichelli, Bologna, 1928.
- Book4 *Fisica ad uso dei Licei*, vol. I, pp. 239 and vol. II, pp. 243, Zanichelli, Bologna, 1929.
- Book5 *Molecole e cristalli*, pp. 303 Zanichelli, Bologna, 1934.
- Book6 *Thermodynamics*, pp. VII-160, Prentice-Hall, New York, 1937.
- Book7 E. Fermi and E. Persico, *Fisica per le Scuole Medie Superiori*, pp. 314 Zanichelli, Bologna, 1938.
- Book8 * *Nuclear Physics. A Course given at the University of Chicago*, Notes compiled by J. Orear, A.H. Rosenfeld, and R.H. Shulter, pp. VII+246, The University of Chicago Press, Chicago, 1949.
- Book9 *Elementary Particles*, pp. XII+110, Yale university Press, New Haven, 1951.

Book10 *Notes on Quantum Mechanics*, pp. VII+171, The university of Chicago Press, Chicago, 1961.

Papers

1921

- P1. [FNM1] *Sulla dinamica di un sistema rigido di cariche elettriche*,
Nuovo Cimento **22**, 199-207 (1921).
- P2. [FNM2] *Sull'elettrostatica di un campo gravitazionale uniforme e sul peso delle masse elettromagnetiche*,
Nuovo Cimento **22**, 176-188 (1921).

1922

- P3. [FNM3] *Sopra i fenomeni che avvengono in vicinanza di una linea oraria*,
Rend. Lincei **31**(1), 21-23, 51-52, 101-103, (1922).
- P4. [FNM4b] *Correzione di una grave discrepanza tra la teoria delle masse elettromagnetiche e la teoria della relatività. Inerzia e peso dell'elettricità*,
Rend. Lincei **31**(1), 184-187 (1922).
- P5. [FNM4b] *Correzione di una grave discrepanza tra la teoria elettrodinamica e quella relativistica delle masse elettromagnetiche. Inerzia e peso dell'elettricità*,
Rend. Lincei **31**(1), 306-309 (1922).
- P6. [FNM38b] *Un teorema di calcolo delle probabilità ed alcune sue applicazioni*,
Tesi di abilitazione della Scuola Normale Superiore. Pisa, 1922.
- P7. [FNM4a] *Über einen Widerspruch zwischen der elektrodynamischen und der relativistischen Theorie der elektromagnetischen Masse*,
Phys. Zeits. **23**, 340-344 (1922).
- P8. [FNM6] *I raggi Rontgen*,
Nuovo Cimento **24**, 133-163, (1922).
- P9. [FNM7] *Formazione di immagini coi raggi Rontgen*,
Nuovo Cimento **25**, 63-68, (1923).
- P10. [FNM14] *Sulla teoria statistica di Richardson dell'effetto fotoelettrico*,
Nuovo Cimento **26**, 97-104, (1923).

1923

- P11. [FNM5] *Le masse nella teoria della relatività*. Da A. Kopff, *I fondamenti della relatività Einsteiniana* Edizione italiana a cura di R. Contu e T. Bembo. Hoepli, Milano 1923, 342-344
- P12. [FNM8] *Sul peso dei corpi elastici*,
Mem. Lincei **14**, 114-124, (1923).
- P13. [FNM9] *Sul trascinamento del piano di polarizzazione da parte di un mezzo rotante*,
Rend. Lincei **32**(1), 115-118, (1923).
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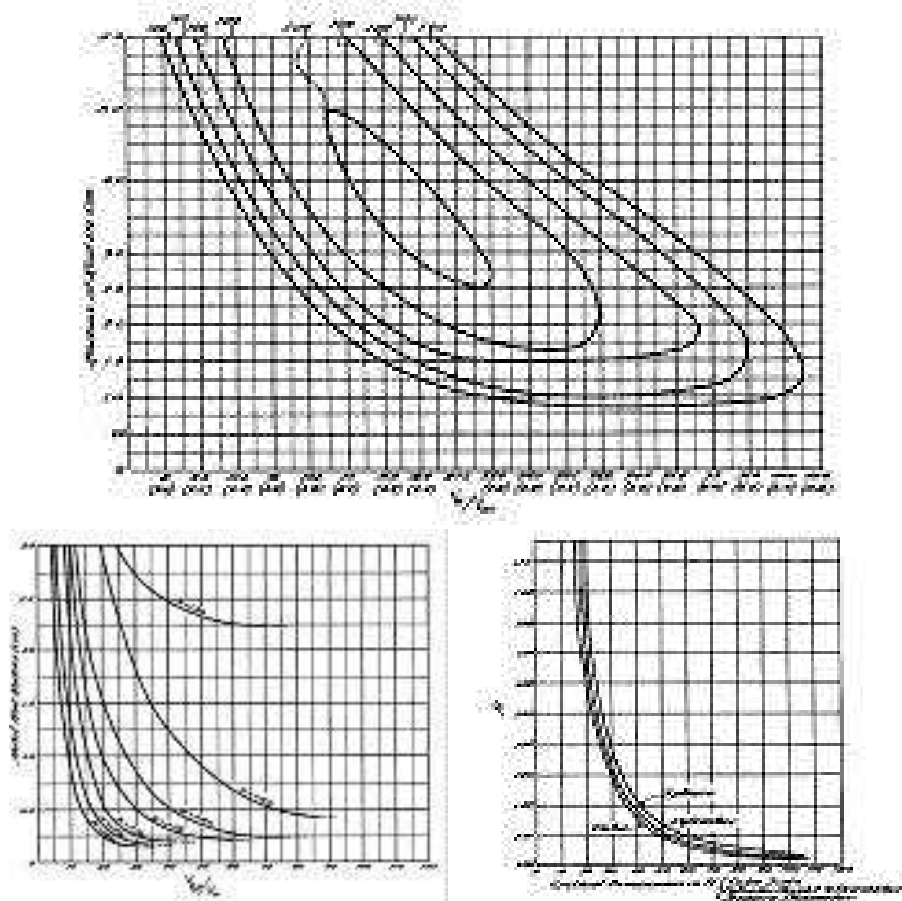


FIGURE 1. Graphs taken from the patent USP3 testifying for the accurate numerical determinations performed by Fermi and collaborators on the physics of nuclear piles. The first two graphs show contour lines representing various reproduction constants k for systems employing uranium oxide (in the form of cylindrical rods) and graphite or systems employing uranium metal rods immersed in heavy water, respectively. The third graph, instead, shows the change in critical size in uranium-graphite reactors with change in k for different geometries.

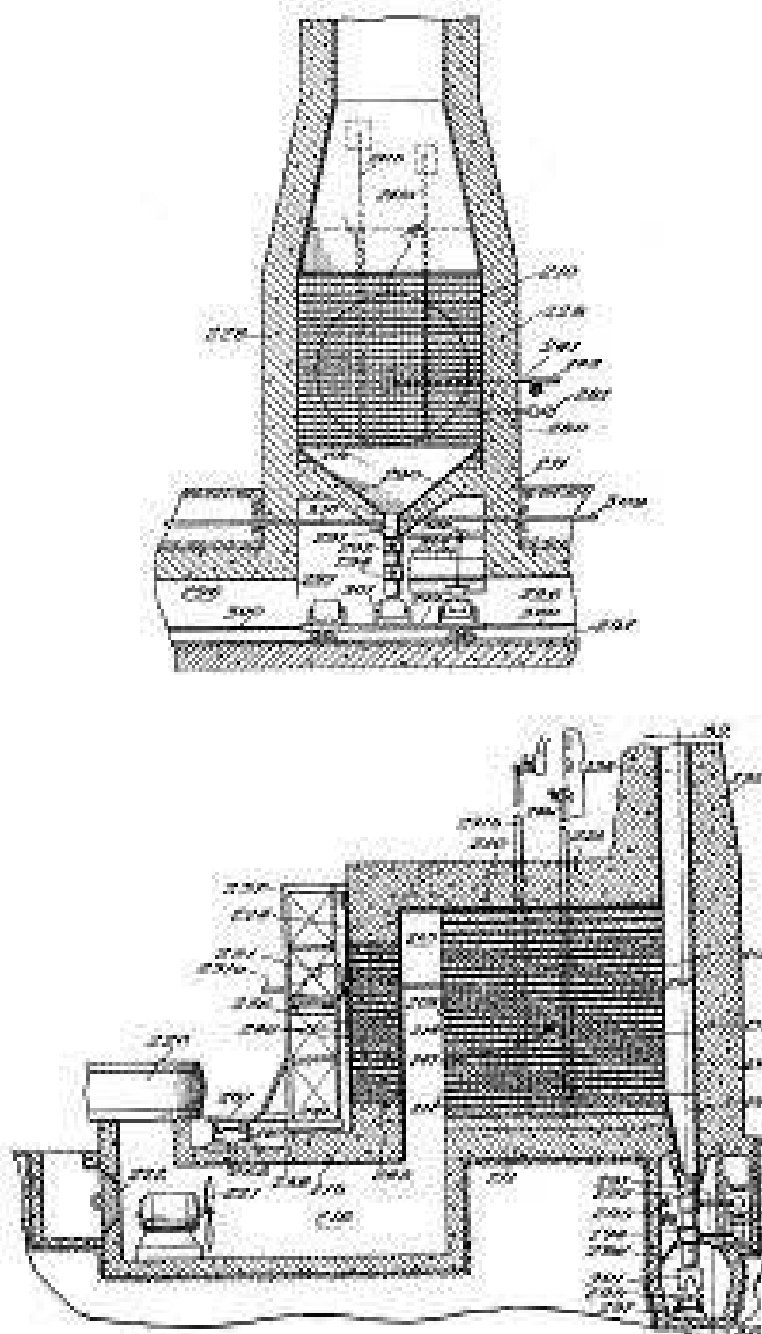


FIGURE 2. Longitudinal and cross sectional views of an air cooled chain reacting system, taken from the patent USP3.

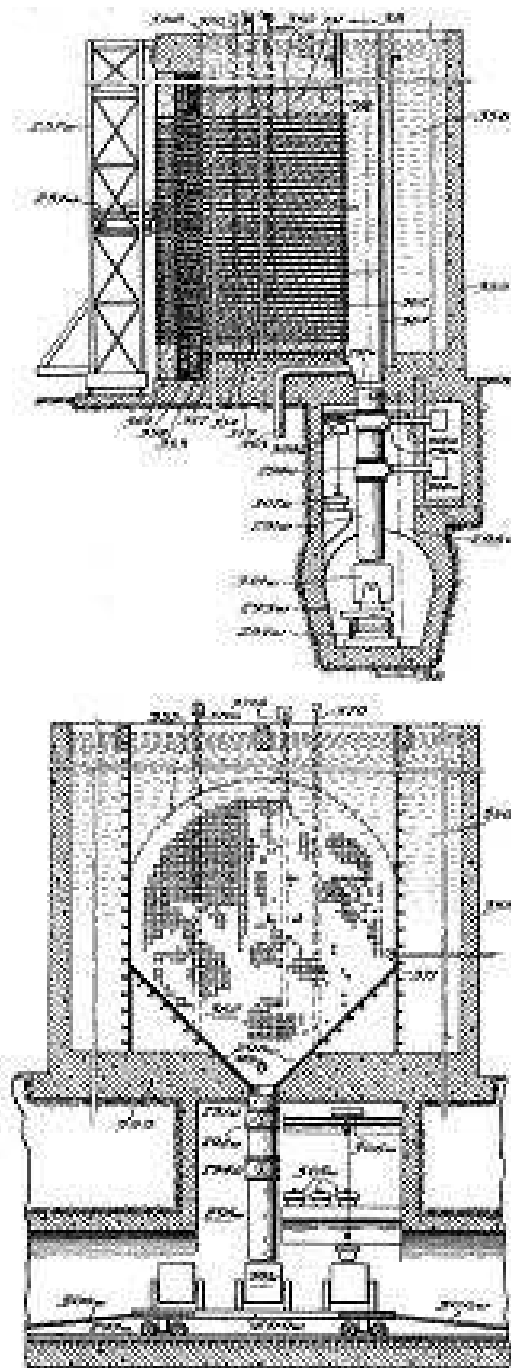


FIGURE 3. Vertical sectional views of a liquid cooled reactor, taken from the patent USP3.

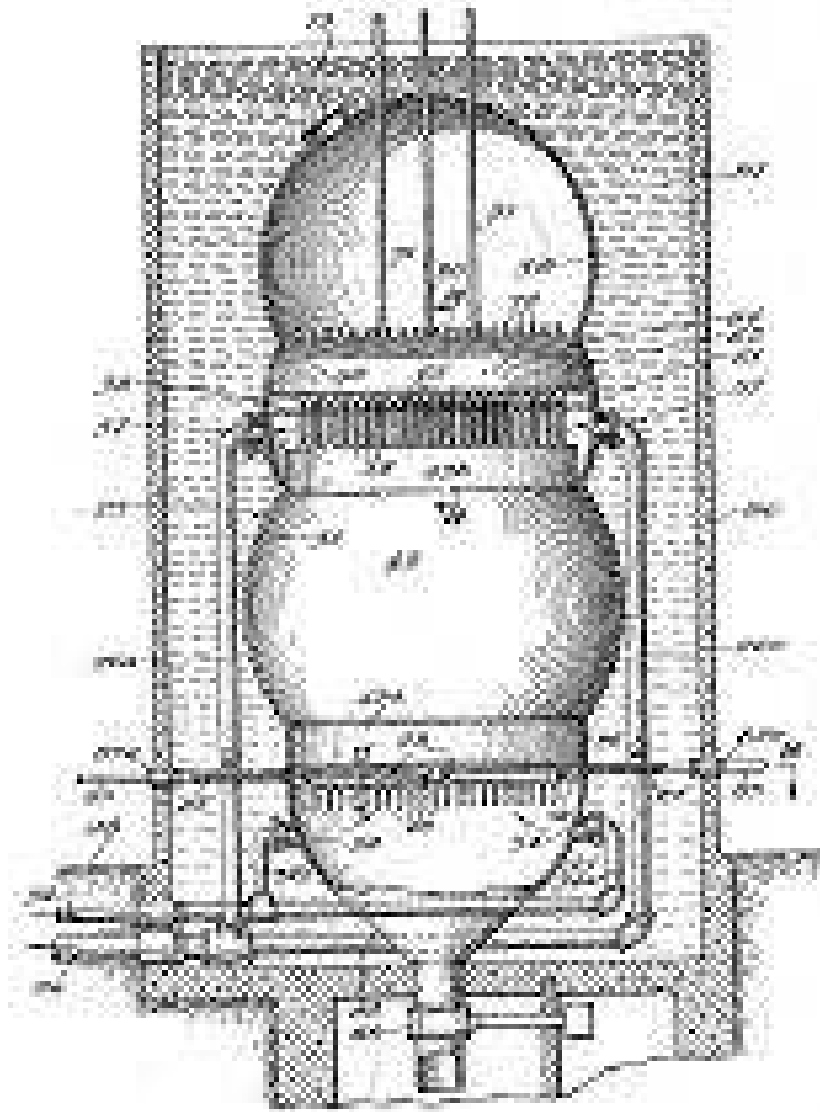


FIGURE 4. A vertical sectional view, taken from the patent USP4, showing a nuclear fission power plant in which the heat equivalent of 100000 kW is removed by circulation of 400000 pounds of helium per hour.

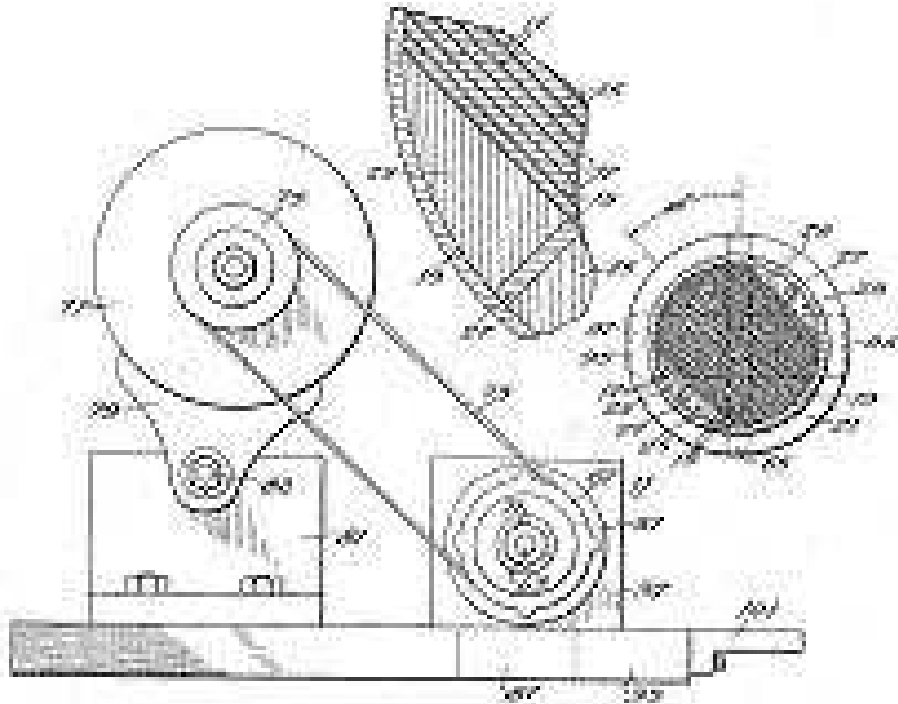


FIGURE 5. A drawing of the rotatable shutter unit and the driving motor of a velocity selector constructed according to what described in the patent USP8.

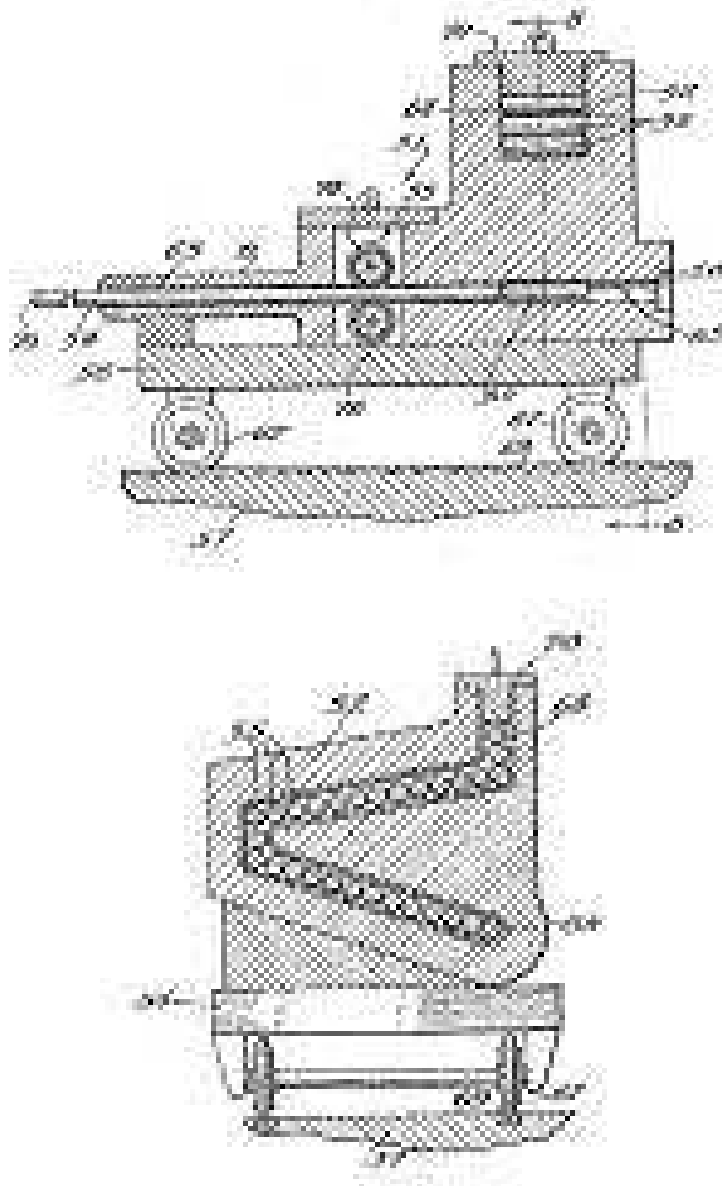


FIGURE 6. The loading device for the air cooled uranium-graphite reactor considered in the patent USP13.

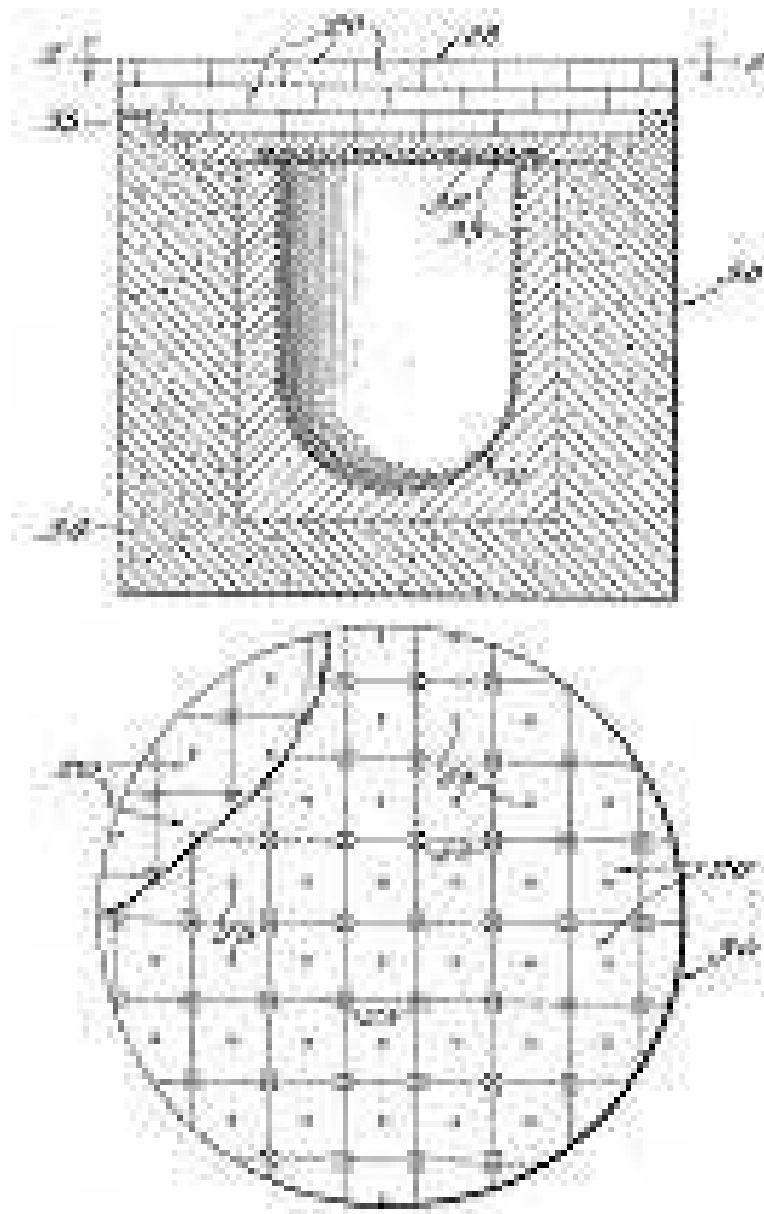


FIGURE 7. Drawings showing the center of a nuclear reactor equipped with a shield constructed according to what described in the patent USP14. In particular, the second figure shows the top construction of the shield mentioned.

S. Esposito: DIPARTIMENTO DI SCIENZE FISICHE, UNIVERSITÀ DI NAPOLI “FEDERICO II” & I.N.F.N. SEZIONE DI NAPOLI, COMPLESSO UNIVERSITARIO DI M. S. ANGELO, VIA CINTHIA, 80126 NAPOLI (Salvatore.Esposito@na.infn.it)

O. Pisanti: DIPARTIMENTO DI SCIENZE FISICHE, UNIVERSITÀ DI NAPOLI “FEDERICO II” & I.N.F.N. SEZIONE DI NAPOLI, COMPLESSO UNIVERSITARIO DI M. S. ANGELO, VIA CINTHIA, 80126 NAPOLI (Ofelia.Pisanti@na.infn.it)